GEM TN-91-00008

GEM Muon System Meeting
Boston University

August 23, 1991

Abstract:

Transparencies from the Muon System Meeting held at Boston University on August 23, 1991

AHLEN

AGENDA FOR GEM MUON SYSTEM MEETING
BOSTON UNIVERSITY
AUGUST 23, 1991

PLACE:
Room 593 of the Physics Research Building at 3 Cummington Street

8:45 AM - Steve Ahlen, Boston U. and Frank Taylor, MIT, INTRODUCTION
9:00 AM - Orrin Fackler, Livermore, "L3 Type Chambers"
9:30 AM - Bob Miller, Michigan State, "Straw Tube Chambers"
10:00 AM - Louis Osborne, MIT, "Limited Streamer Tubes"

10:30 AM - Coffee Break

11:00 AM - Irwin Pless, MIT, "RPC's, and Trigger Issues"
11:30 AM - Scott Whitaker, Boston U., "Pad Chambers"
12:00 PM - Bing Zhou, Boston U., "Pressurized Drift Tubes"

12:30 PM - Lunch

1:30 PM - Roy Weinstein, U. Houston, "Gas Tests and CERN Beam Tests of Limited Streamer Tubes"
2:00 PM - Roger McNeil, LSU, "Simulations for High Field Option"
2:30 PM - Andrey Korytov, Dubna/MIT, "Fermilab Beam Tests"
3:00 PM - Steve Ahlen, Boston U., "Organization for Muon System"
3:15 PM - Jim Sullivan, MIT, "Momentum Resolution Calculations"
3:30 PM - Frank Nimblett, Draper, "Engineering Plan and Comparisons for Several Chamber Technologies"
3:45 PM - Jack Hanlon, Los Alamos, "Alignment Strategies"
4:00 PM - Eric Hazen, Boston U., "Muon System Electronics"

4:15 PM - Break

4:30 PM - Discussion:
- a) Chamber Technologies: pros and cons of each
- b) System Philosophy:
  - i) Multiple vs. single technolgies
  - ii) Projective vs. non-projective tracking
- c) Preferred magnet configuration:
  - i) What value of B?
  - ii) How non-uniform can (should) B be?
  - iii) Should chambers be outside magnet?
- d) Plan for making progress in the muon system:
  - i) Reduction in technolgies
  - ii) Interactions with other systems (i.e. mechanisms for recommending preferances on magnet, tracking, etc.)
  - iii) Crucial R&D for LoI

6:00 PM - Meeting Adjourns

G-EM Muon Meeting Attendance

Name	Institution	e-mail	Phone
Steve Allen	Boston U.	jnt% "allen@bupkyc"	617-353-8940
Orin Fackler	Lawrence Livermore	FACKLER@REG.LLNL.GOV	510 after Sept. 1 415-423-1766
Roger McNeil	LSU	PHMCNE@LSUVAX	504-388-6857
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Winston Ko	U.C. Davis	KO@UCDHEP	916-752-1283
Frank Taylor	MIT	FET@SLACVM	617-253-7582
COLEMAN JOHNSON	UC Lawrence Livermore Natl Lab	JOHNSON@TROY.LLNL.GOV	(415) 422-8748 (510) After Sept 1
GARY DEIS	UC/LLNL	DEIS1@LLNL.GOV IGW::TROY::DEIS	(415) 423-7533 (510 after 9/1)
Craig R. Wuest	LLNL	IGW::EDSEQ1::WUEST WUEST@LLNL.GOV	(510) 423-2909
Andrey Korytov	JINR/MIT	FNAL::KORYTOV	(708) 840-3439
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Scott Whitaker	BU	SCOTT@BUPHYC	617-353-8916
Bob Wilson	BU	WILSON@BUPHYC	[illegible]
Jim SHANK	BU	SHANK@BUPHYC	617 353 602
Bob Miller	MSU	MSUHEP::MILLER	517-353-16[illegible]
Brian Eason	Martin Marietta	BWEASON@SIM.DEN.MMC.COM	(303) 977-222[illegible]
Frank Nimblett	Draper Lab.	NIMBLETT@DRAPER.COM	(617) 258-139[illegible]
Larry Sulak (liaison with calorimetry for this meeting)	Boston	BUPHYC::SULAK	" 353-9454
Jack Hanlon	Los Alamos		505-667-5828
Brian Smith	Los Alamos	BSMITH@CHEVAK.MEEDIV.LANL.GOV	505-665-[illegible]
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George Zapalac	BU	GOZ at BUPHY.BU.EDU	(617) 353-2189
AL MASCHKE	SSCL	MASCHKE@Ssc.gov	(214) 705-3069

Name	Institution	e-mail	Phone
John Hoftiezer	LeCroy	DUPHYC::LeCroy	914-578-6015
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Michal Seman	Columbia Univ Nevis Lab.	NEVIS::SEMAN	914-591-8100 ext 23
Jim Sullivan	MIT	MITLNS::SULLIVAN	617-253-7537
Alix Marin	B.U.	BUPHYC::MARIN	617-353-9133
Bing Zhou	BU	BUPHYC::ZHOU	617-353-5102
Dinesh Loomba	BU	BUPHYC::DINESH	617-353-6640
Spencer Klein	BU/UCSC	BUPHYC::SPENCER	617-353-602.
Bill Worstell	BU	BUPHYC::WORSTELL	617-353-9584
Pete Lander	UCD	UCDHEP::LANDER	916 752-1[illegible]

Introduction by

Steve Ahlen

FROM DARION AND
WILLIS, Aug 8, 1991

Objectives and Priorities of Groups:

- should have longer view than Lo
- should make technology choices
- should develop/implement plan for R+D, Engineering, beam tests

Cost Guidelines:

• Magnet	100M
• Muon	130M
• Large Structures	20M
• Calorimeters	150M
• Tracker	40M
• Trigger	10M
• Computing	10M
• R+D	40M
	500M

MUONS, Ahlen, Taylor

Should take into account:

- spatial resolution
- triggering
- F/B problems ($\vec{B}$ shaping)
- Upgrade options (outside magnet)
- manufacturing plan

FOR October 3-4 REVIEW BY PAC:

- FOCUS ON TWO TECHNOLOGIES WITH DETAILED PROTOTYPE AND ENGINEERING PLAN

FOR November 30 LoI:

- BASELINE SYSTEM WITH DEFENDABLE PERFORMANCE AND COST
- WELL DEFINED R+D AND ENGINEERING PLAN FOR FY92

CHAMBER TECHNOLOGIES

1) Description of technique

2) References to development and use

3) Specs on actual systems used in past

4) "Actual" performance in Baseline Barrel:

$L = 29\,m$
$IM = 16.6\,m$
$HC = 10\,m$ long by $7.4\,m$ diameter
$\vec{B}$ is uniform
$B = 0.8\,T$

Using 8+16+8 tracking layers

5) Description of F/B strategy

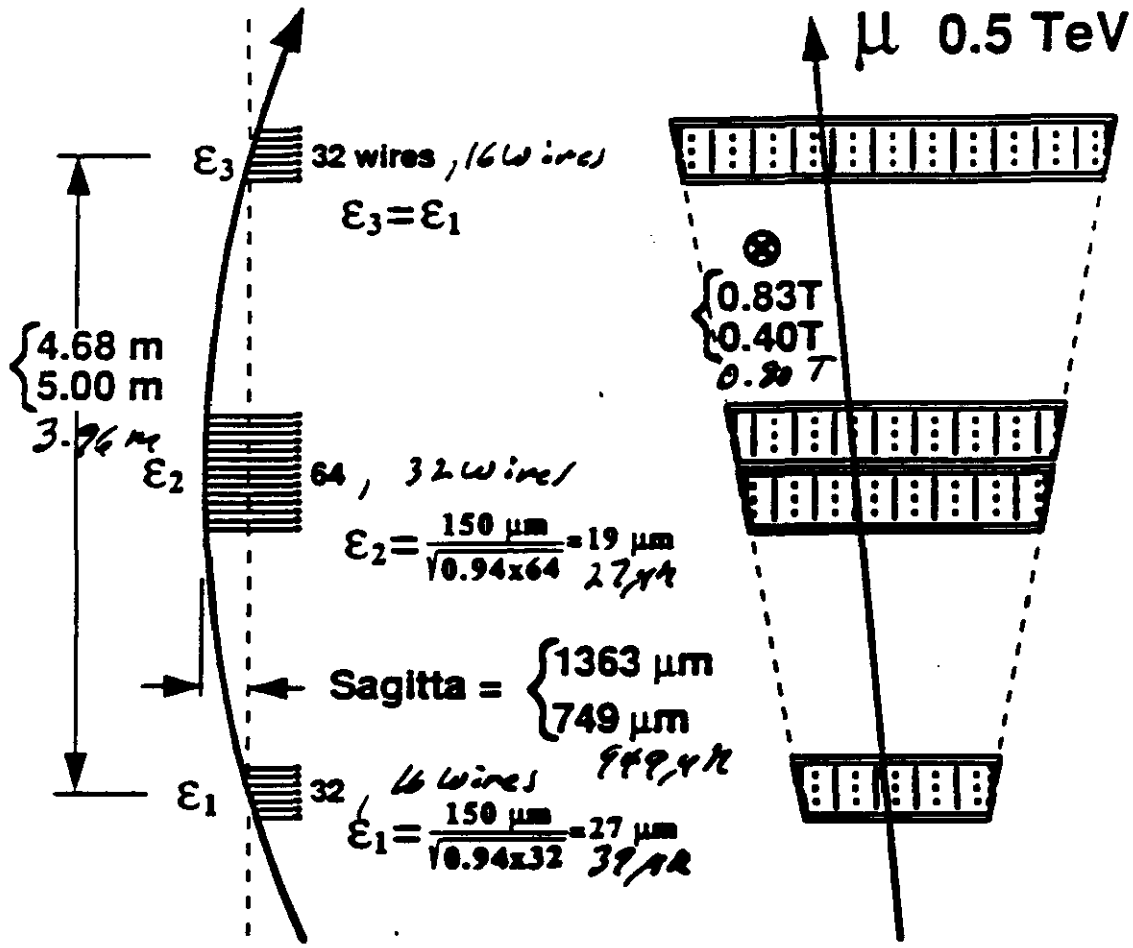
6) Anticipation of technology improvement/development

7) Critical R+D

Talk by Orrin Fackler

on L3-Type Chambers

L★ GEM



$$\Delta S=\sqrt{\frac{1}{2}\times\varepsilon_1^2+\varepsilon_2^2+\Delta S_{sys}{}^2+\Delta S_{ms}{}^2}$$

$$=\sqrt{\frac{1}{2}\times 27\,\mu m^2+19\,\mu m^2+20\,\mu m^2+15\,\mu m^2}$$

$$=37\,\mu m \text{ , } 43.8\,\mu m$$

$$\frac{\Delta S}{S}=\begin{cases}2.8\% & \text{Superconducting}\\ 4.9\% & \text{Normal}\end{cases}$$

4.6% GEM

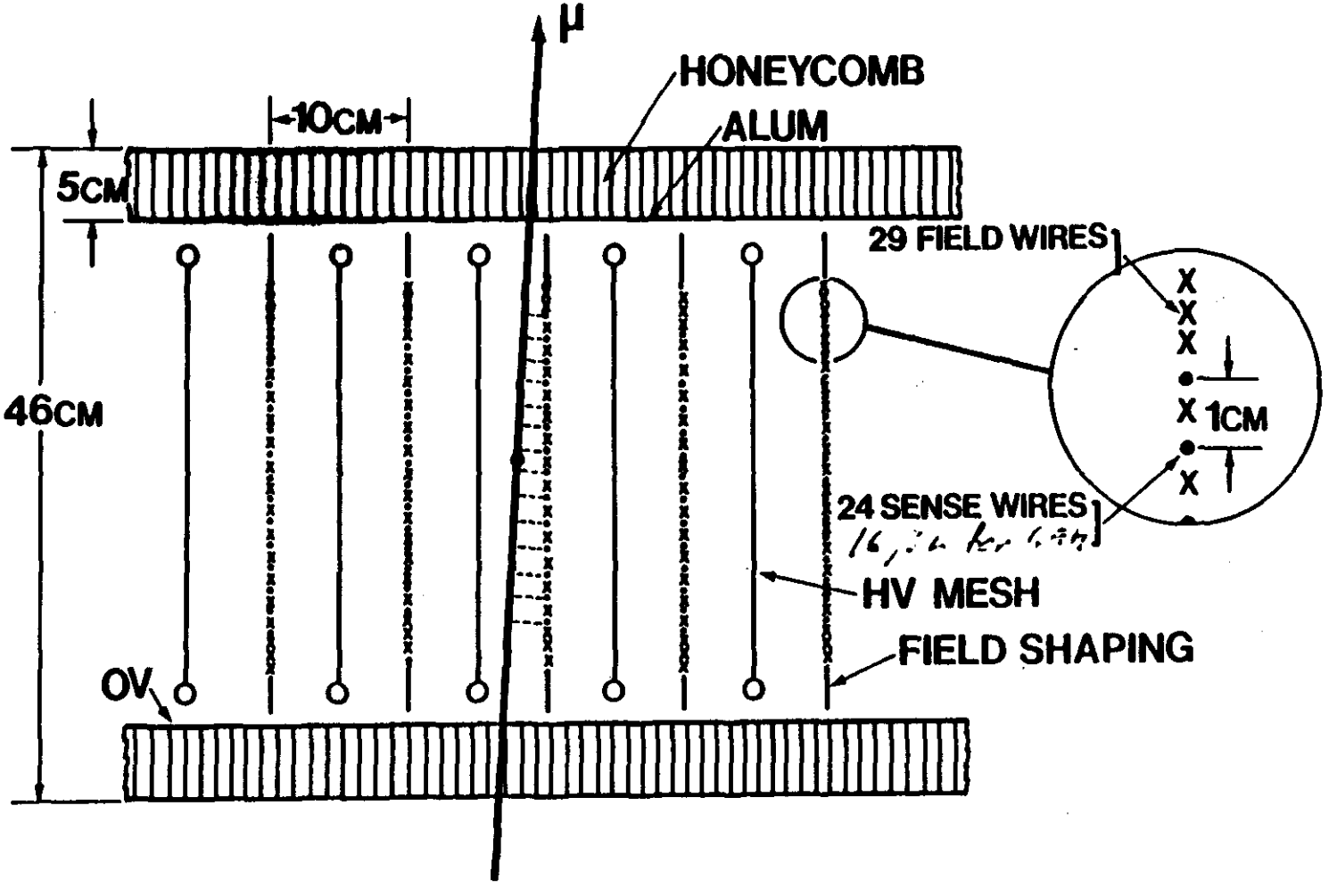

μ
HONEYCOMB
ALUM
10CM
5CM
46CM
29 FIELD WIRES
1CM
24 SENSE WIRES
HV MESH
FIELD SHAPING
OV

FIG. 13

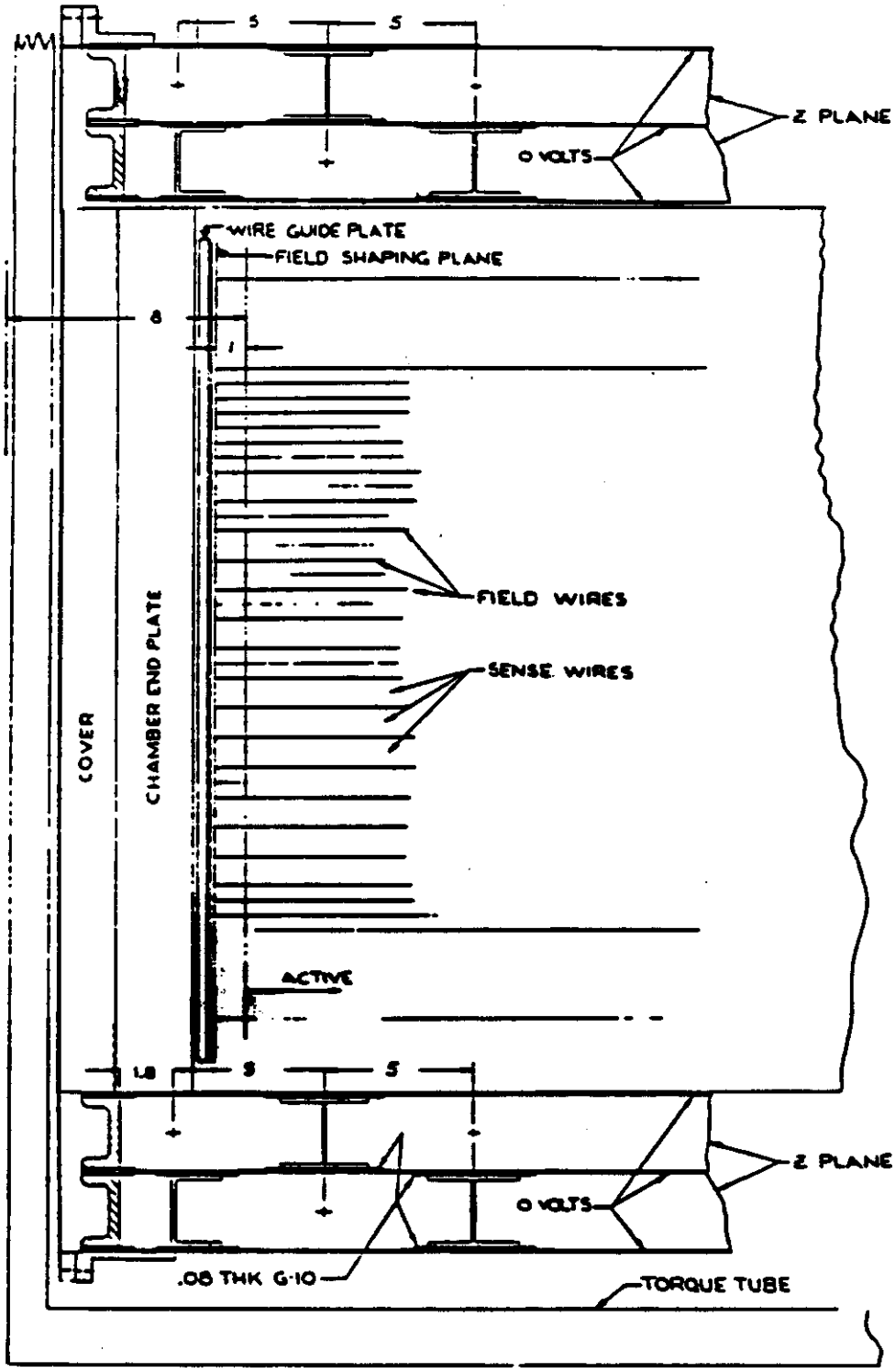
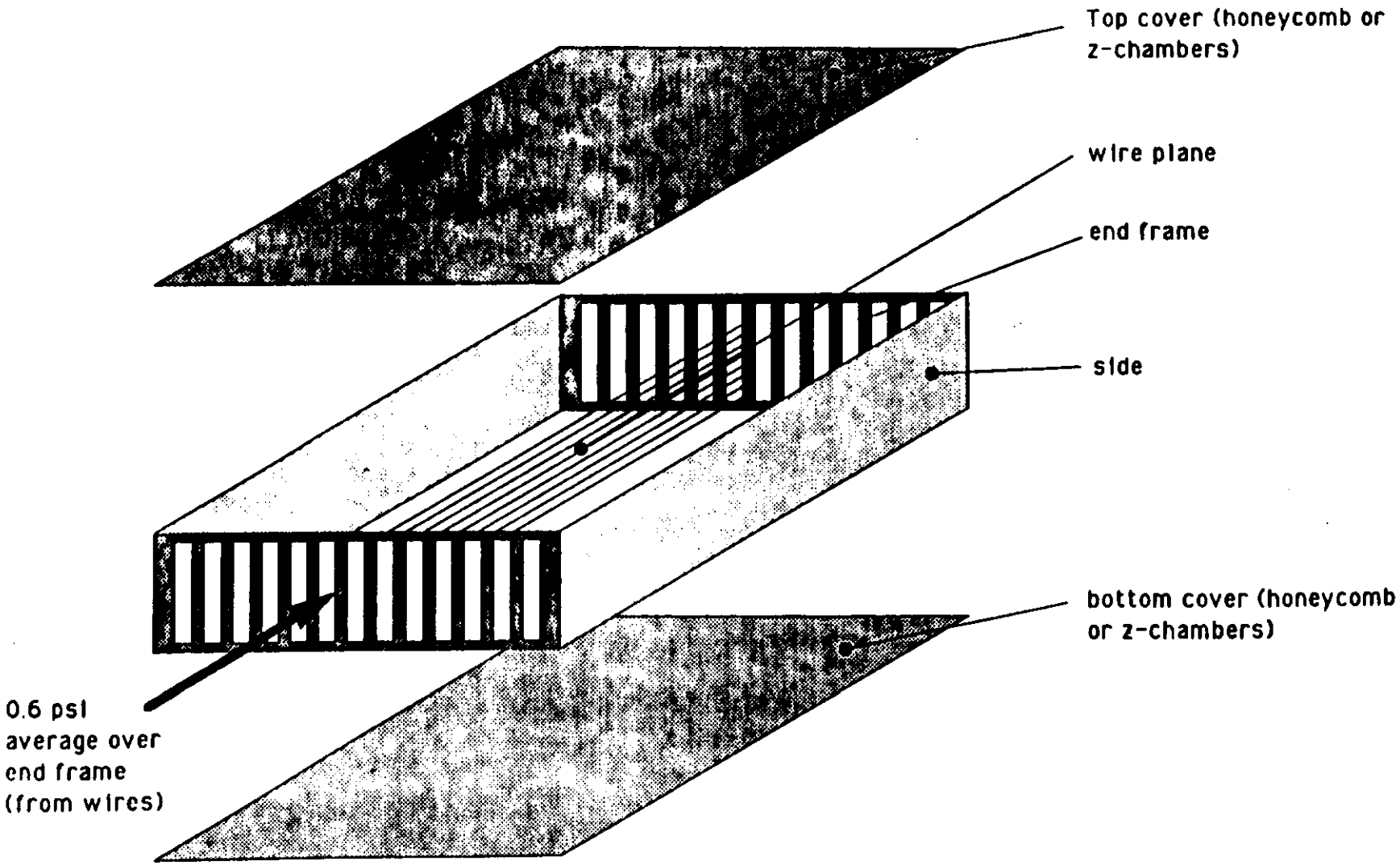
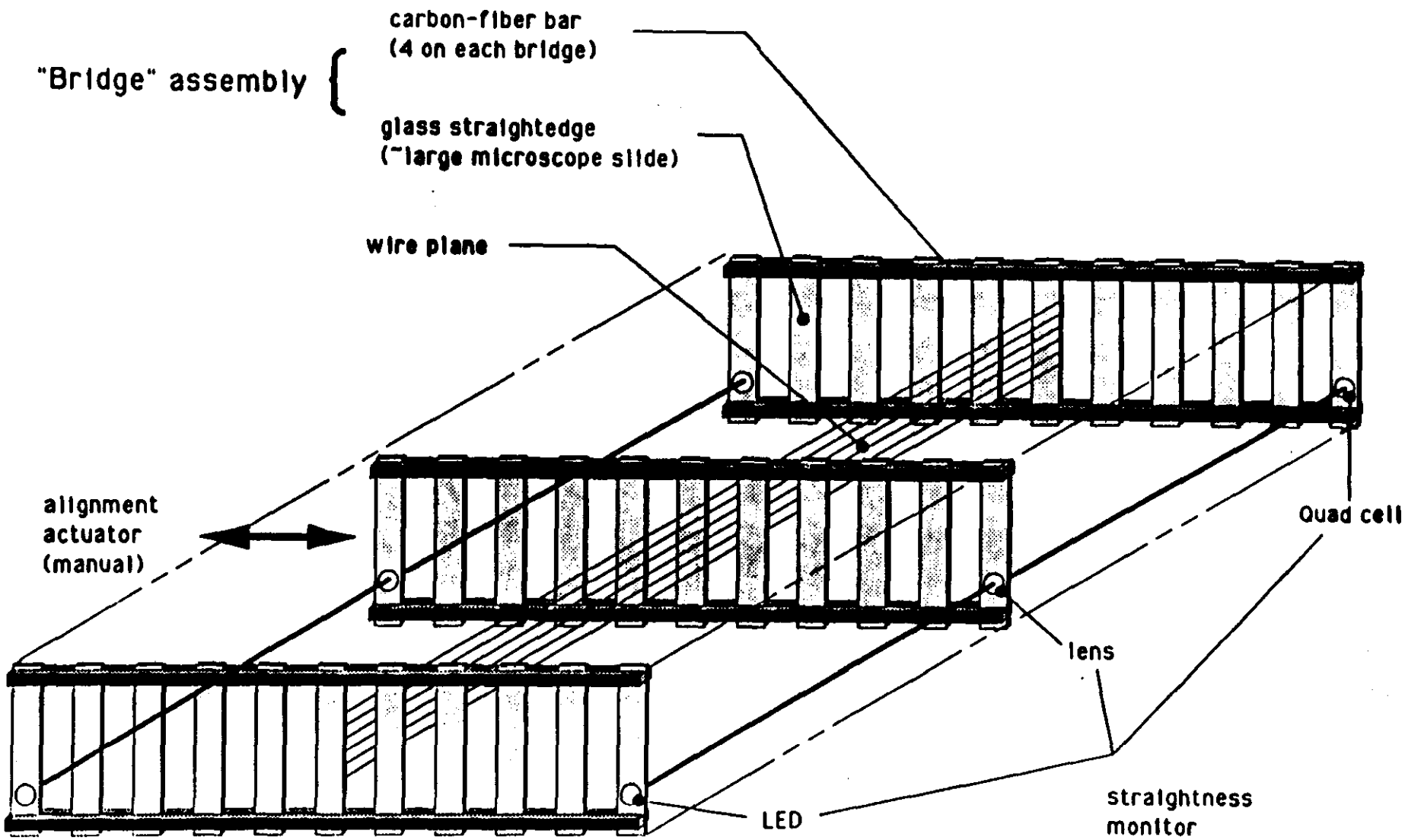

5
5
Z PLANE
0 VOLTS
WIRE GUIDE PLATE
FIELD SHAPING PLANE
8
1
FIELD WIRES
SENSE WIRES
COVER
CHAMBER END PLATE
ACTIVE
1.8
5
5
Z PLANE
0 VOLTS
.08 THK G-10
TORQUE TUBE

FIG.19

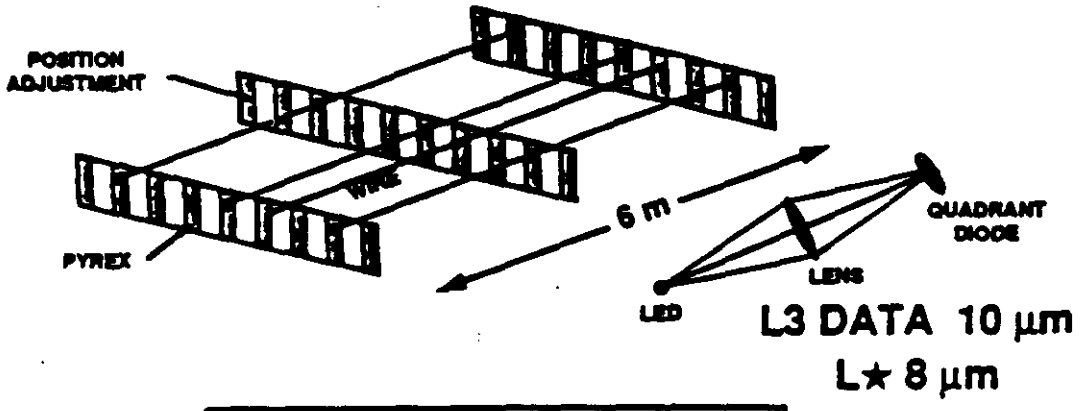
Muon Chamber - basic load-bearing structure



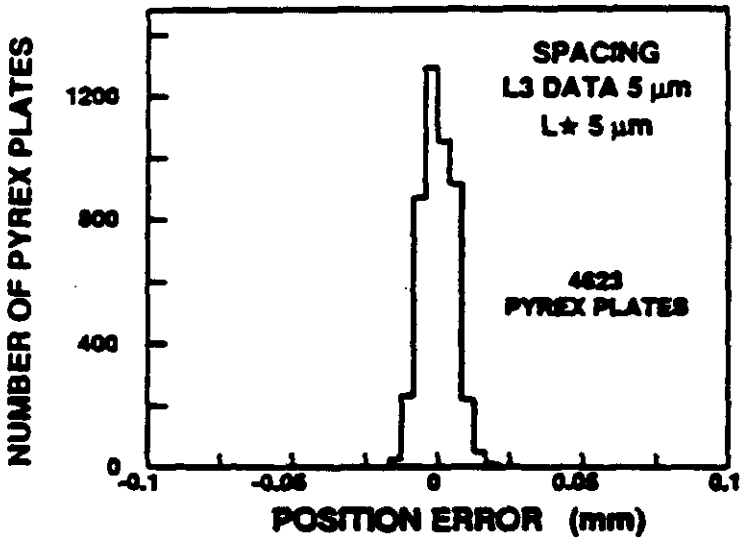
Muon Chamber - wire plane alignment structure



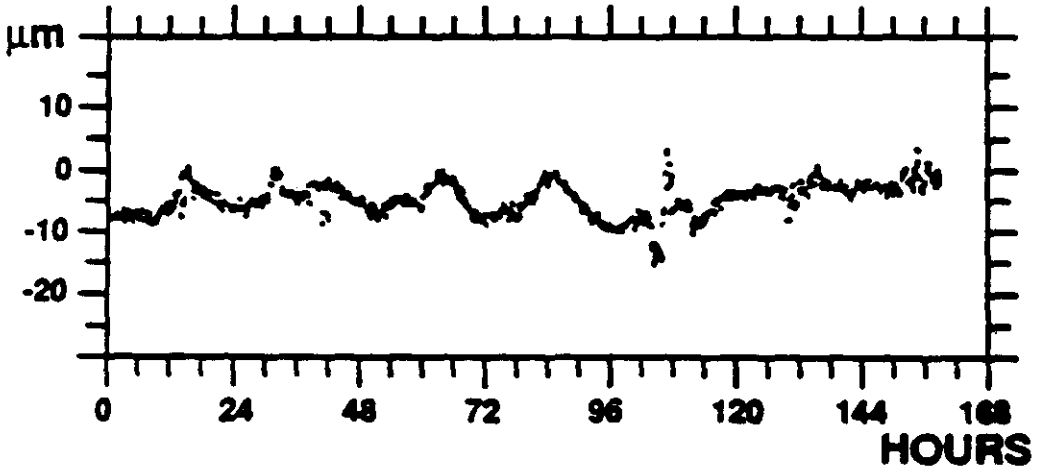
L3 AND L★
WIRE POSITIONING ACCURACY

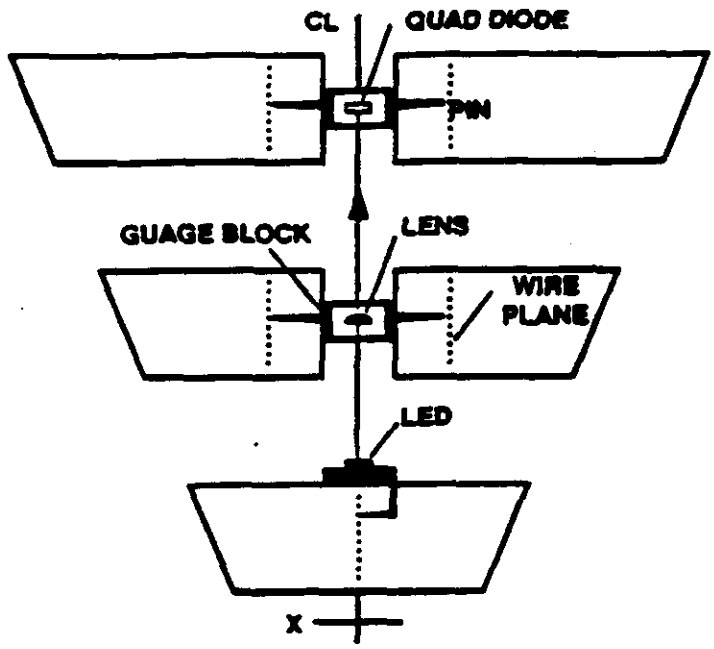


L3 DATA 10 μm
L★ 8 μm



X STRAIGHTNESS MONITOR

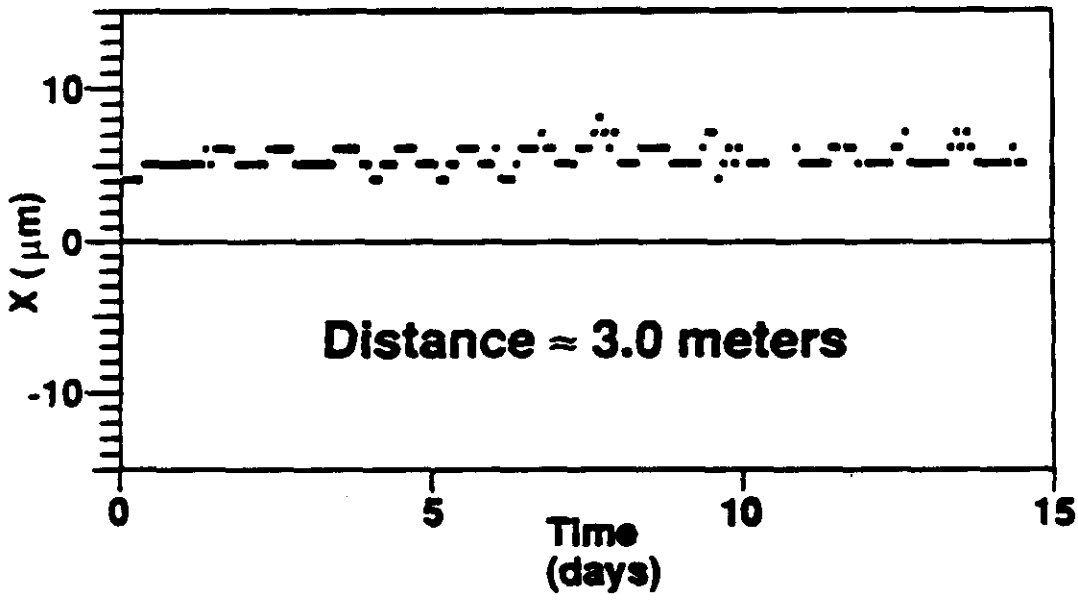




Stability of L3 Alignment for 3 Layers of Chambers

4μm

Reproduces after 1 Year



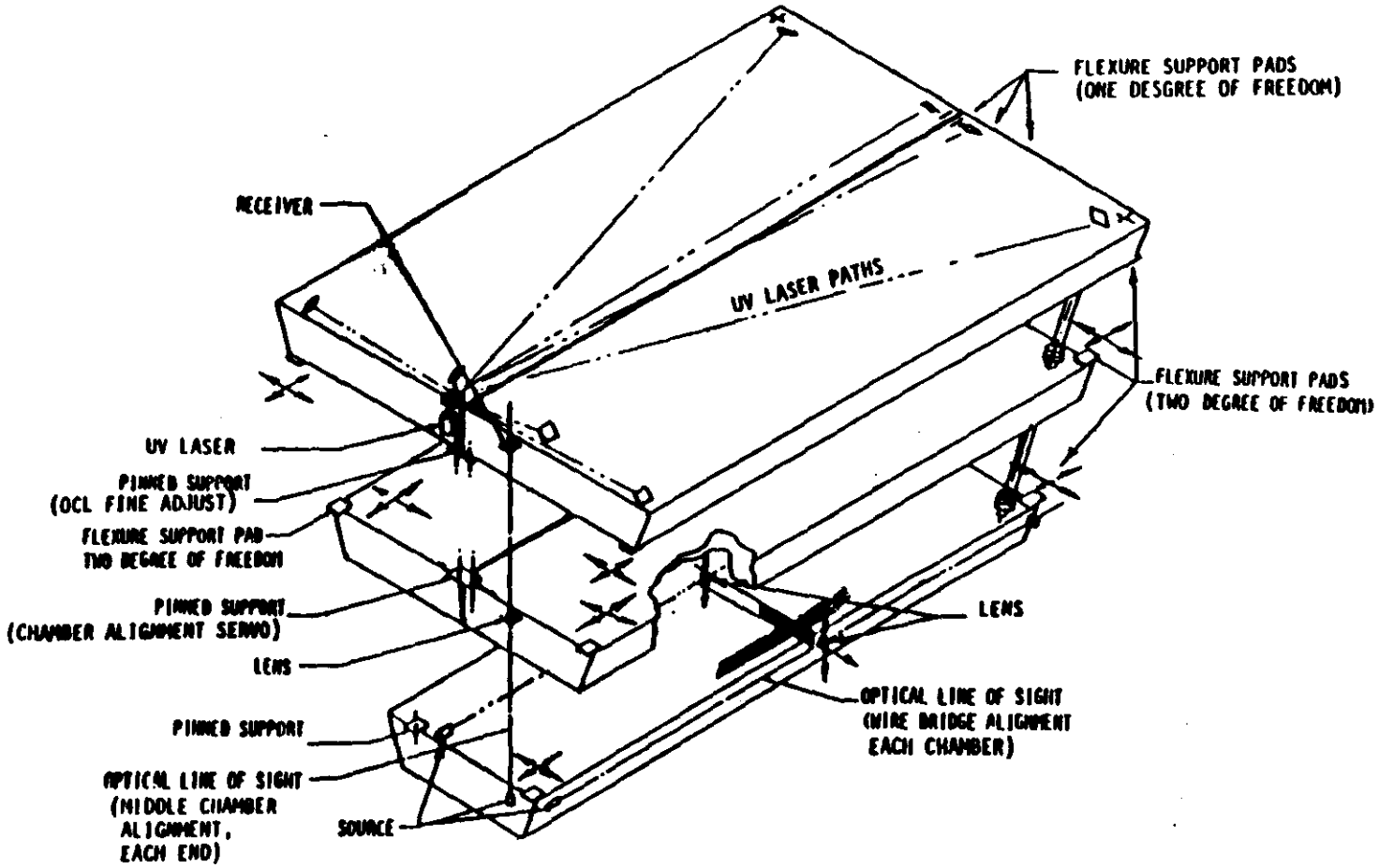
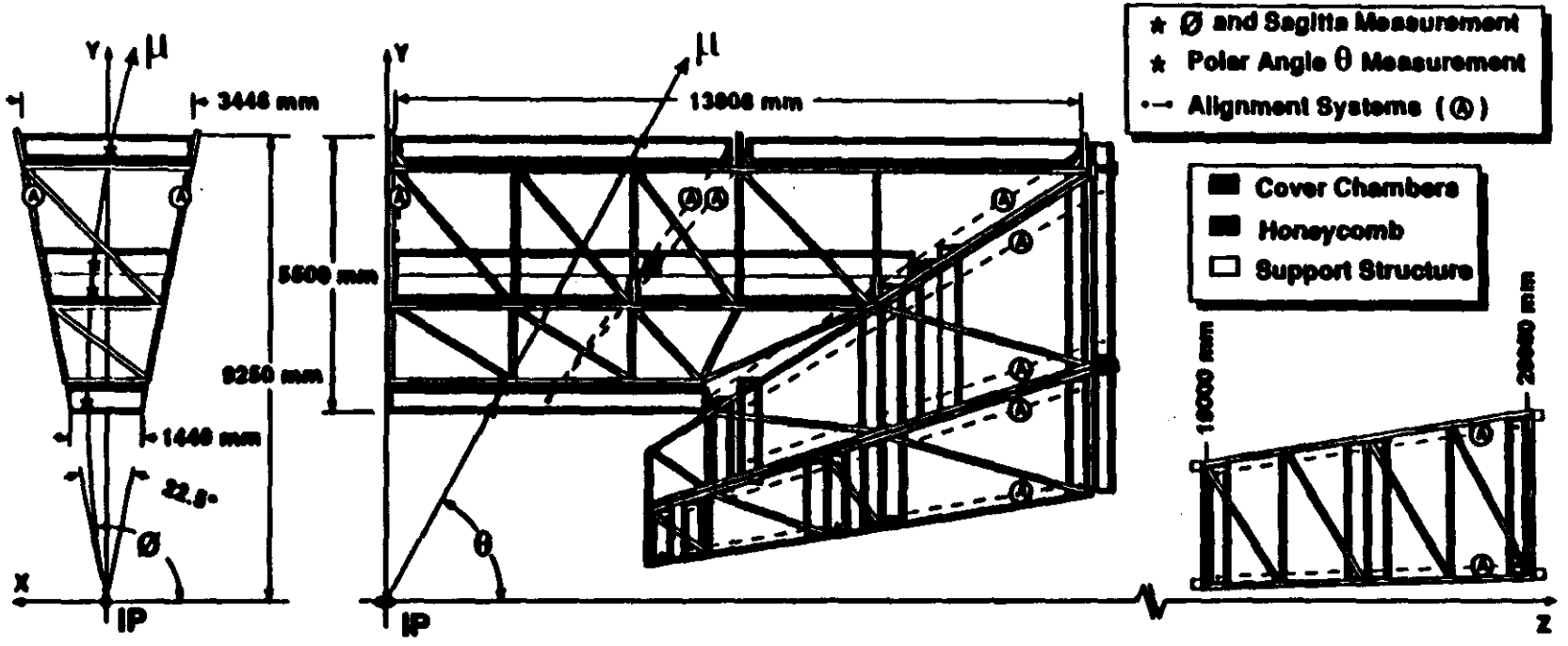

FLEXURE SUPPORT PADS
(ONE DESGREE OF FREEDOM)
RECEIVER
UV LASER PATHS
FLEXURE SUPPORT PADS
(TWO DEGREE OF FREEDOM)
UV LASER
PINNED SUPPORT
(OCL FINE ADJUST)
FLEXURE SUPPORT PAD
TWO DEGREE OF FREEDOM
PINNED SUPPORT
(CHAMBER ALIGNMENT SERVO)
LENS
LENS
PINNED SUPPORT
OPTICAL LINE OF SIGHT
(WIRE BRIDGE ALIGNMENT
EACH CHAMBER)
OPTICAL LINE OF SIGHT
(MIDDLE CHAMBER
ALIGNMENT,
EACH END)
SOURCE

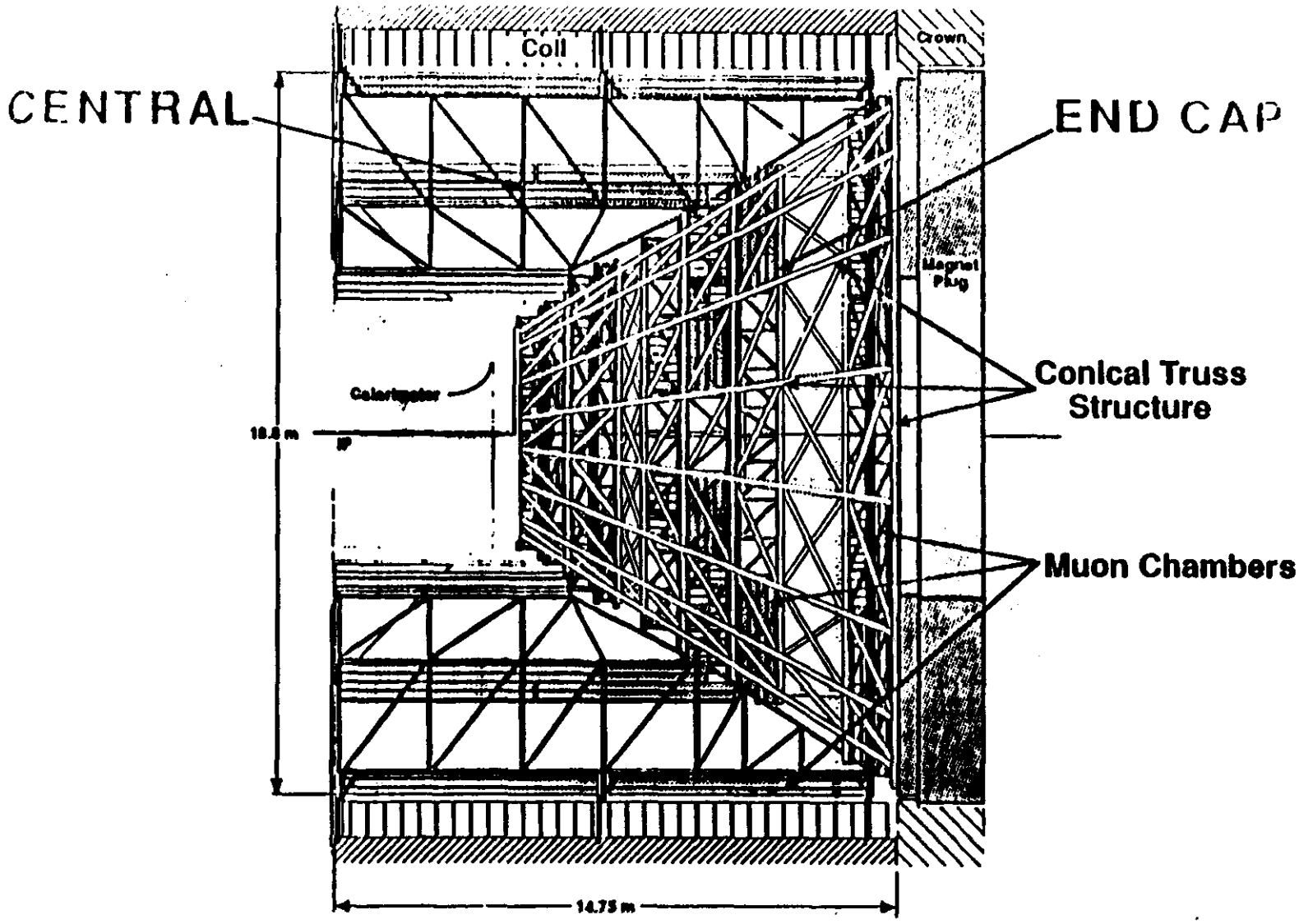
FIG.16

L* Alignment

	L*	L3 - Achieved
P- Measurement 3 Layers - Absolute Monitored - Relative	8 μm 1 μm	10 μm 0.2 μm
Global All tracks point to intersection	0.7 mm	1.0 mm



Sectional view of the L★ Muon Detector



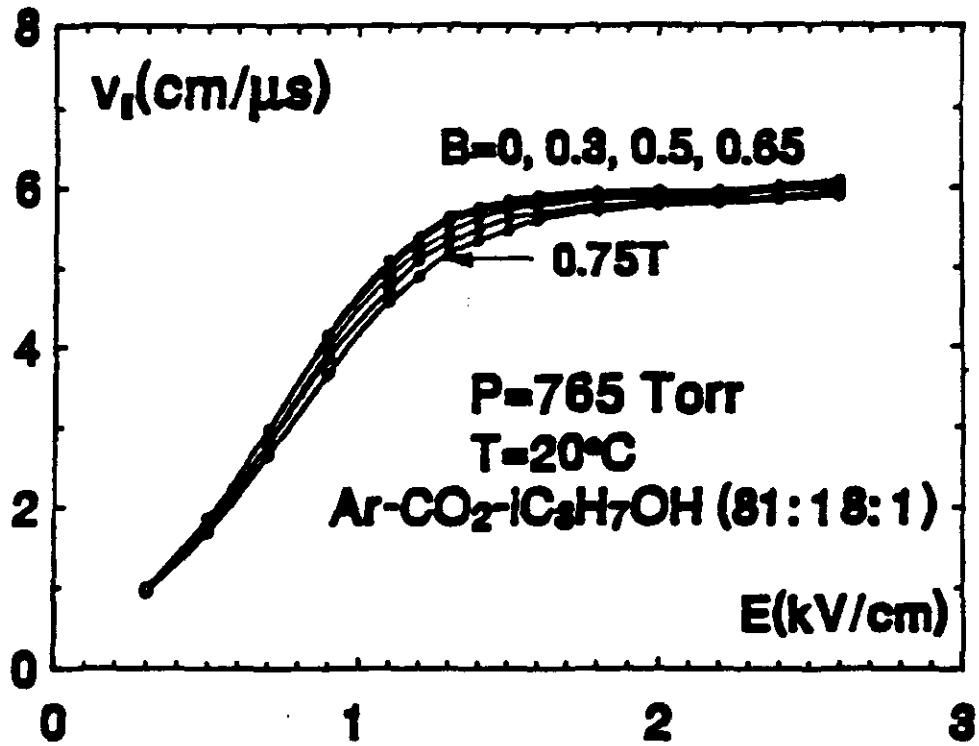
STABLE, KNOWN TO ≤ 20μm

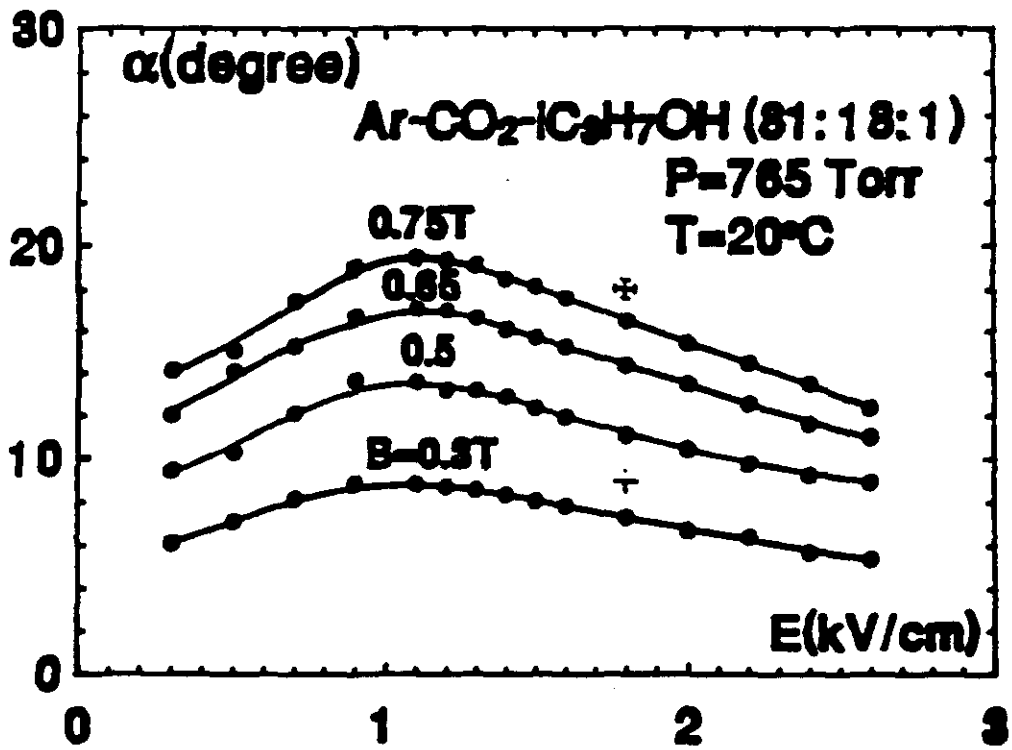
Muon Chamber Gas Studies

- Goal: Characterize and identify a suitable gas for the muon chambers
  - Insensitive to small changes in E-field and composition
  - Non-flammable (V = 2000 m^3)
  - Sparkproof
  - Slow aging
  - Small Lorentz deflection angle
  - Low cost

NEW SINCE EoI

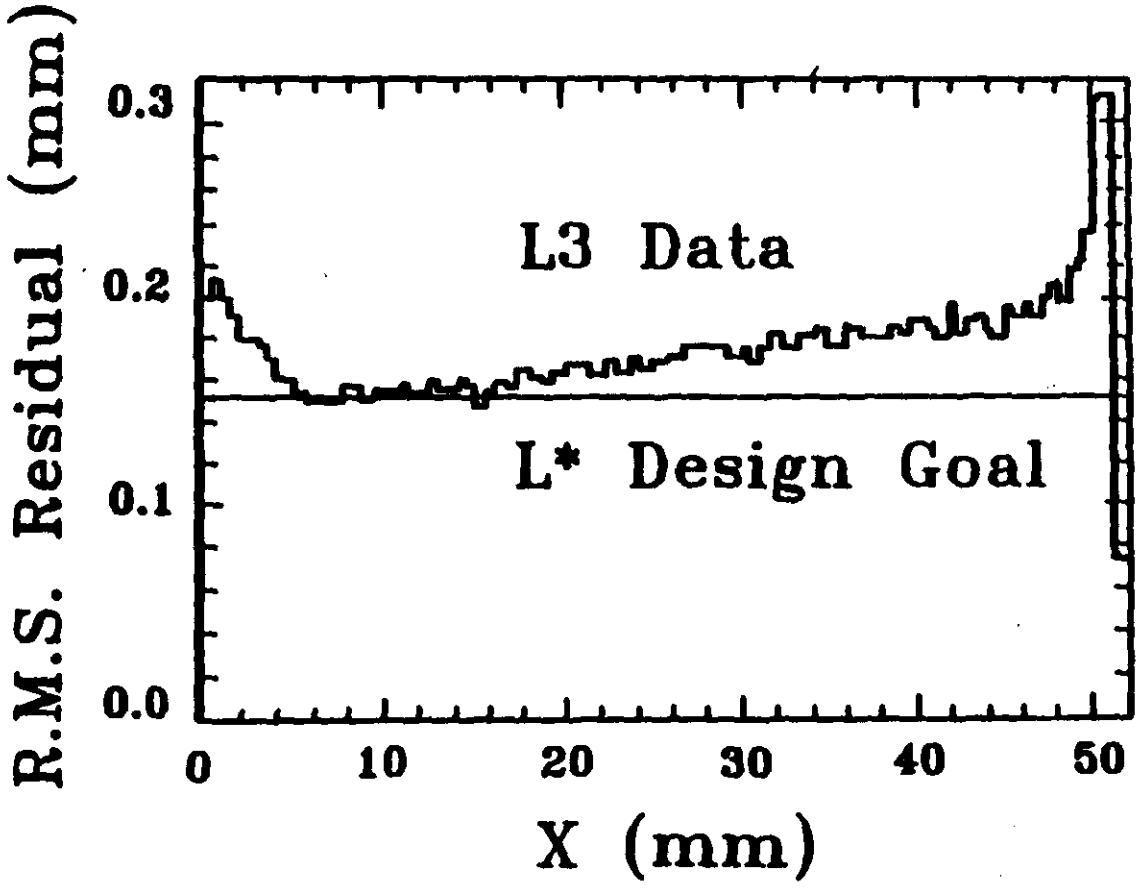
9/90



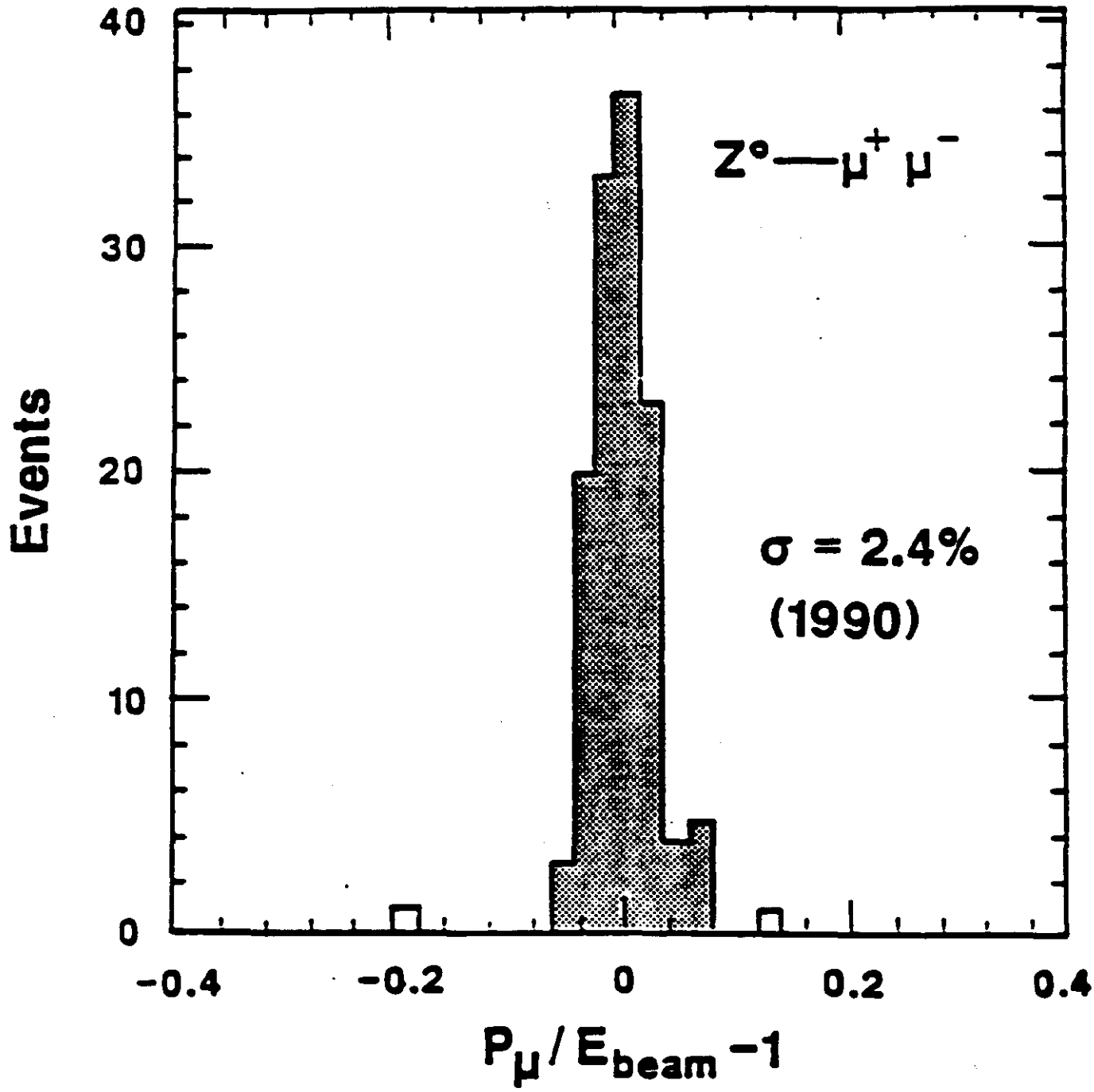


CANDIDATE GAS

L* Single Wire Resolution



Muon Momentum Resolution



- Design Resolution from Technical Proposal 2.38% (1982)

GEM Baseline Design

	A	B	C	D	E	F	G	H	I	J
1										
2	B =	0.8								
3	L=	3.958								
4	n1,3 =	16								
5	BL2 =	12.53								
6	theta =	1.57079633								
7										
8			single-wire	wire						
9	P (GeV)	sagitta	resolution(um)	efficiency	eps1,3	eps2	eps,sys	eps,ms	sag error	res(%)
10	1	474720	150	1.00	37.50	26.52	20.00	2127.03	2127.46	0.45
11	100	4747	150	1.00	37.50	26.52	20.00	21.27	47.53	1.00
12	500	949	150	1.00	37.50	26.52	20.00	4.25	42.71	4.50
13	1	474720	150	0.94	38.68	27.35	20.00	2127.03	2127.48	0.45
14	100	4747	150	0.94	38.68	27.35	20.00	21.27	48.46	1.02
15	500	949	150	0.94	38.68	27.35	20.00	4.25	43.75	4.61
16										
17	1	474720	200	1.00	50.00	35.36	20.00	2127.03	2127.71	0.45
18	100	4747	200	1.00	50.00	35.36	20.00	21.27	57.90	1.22
19	500	949	200	1.00	50.00	35.36	20.00	4.25	54.02	5.69
20	1	474720	200	0.94	51.57	36.47	20.00	2127.03	2127.75	0.45
21	100	4747	200	0.94	51.57	36.47	20.00	21.27	59.26	1.25
22	500	949	200	0.94	51.57	36.47	20.00	4.25	55.48	5.84

Muon Momentum Resolution

Standard Trial Configuration

	A	B	C	D	E	F	G	H	I	J
1										
2	BL2=	13								
3	n1,3=	8								
4	L=	4.03								
5	theta=	1.57079633						1		
6			single-wire	wire						
7	P(GeV)	sagitta	resolution (um)	efficiency	eps1,3	eps2	eps, sys	eps,ms	sag error	res (%)
8	1	492424	150	1.00	53.03	37.50	20	2165.73	2166.47	0.44
9	100	4924	150	1.00	53.03	37.50	20	21.66	60.68	1.23
10	500	985	150	1.00	53.03	37.50	20	4.33	56.84	5.77
11	1	492424	150	0.94	54.70	38.68	20	2165.73	2166.51	0.44
12	100	4924	150	0.94	54.70	38.68	20	21.66	62.14	1.26
13	500	985	150	0.94	54.70	38.68	20	4.33	58.40	5.93
14										
15										
16	1	492424	200	1.00	70.71	50.00	20	2165.73	2166.97	0.44
17	100	4924	200	1.00	70.71	50.00	20	21.66	76.61	1.56
18	500	985	200	1.00	70.71	50.00	20	4.33	73.61	7.47
19	1	492424	200	0.94	72.93	51.57	20	2165.73	2167.05	0.44
20	100	4924	200	0.94	72.93	51.57	20	21.66	78.67	1.60
21	500	985	200	0.94	72.93	51.57	20	4.33	75.75	7.69

$B = 0.8T$

8-16-8 Sense Wires

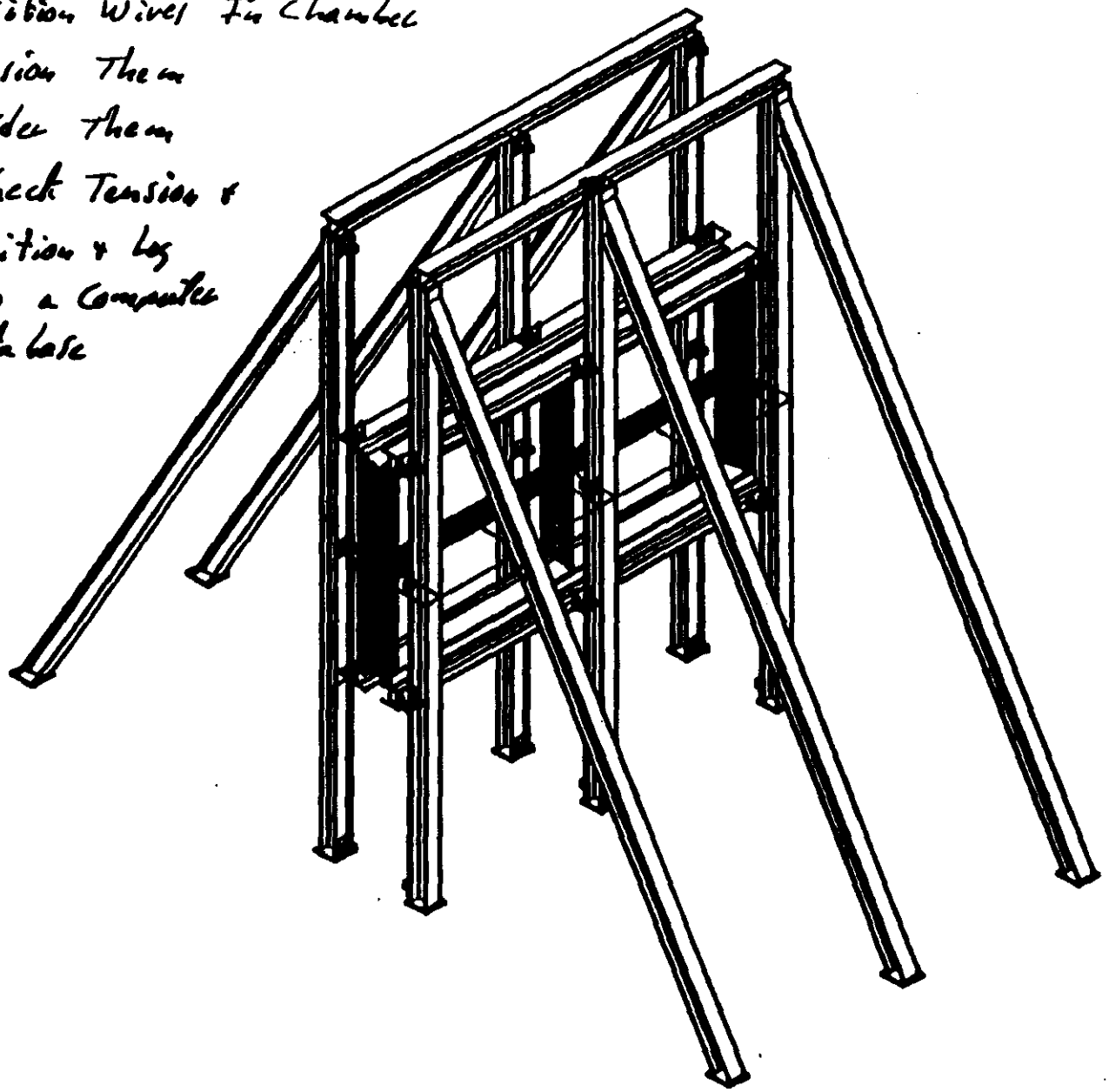
50 mm Clearance Barrel → Muon + Muon → Magnet (16 Sectors)

Inner/Outer Chamber Thickness = 311 mm

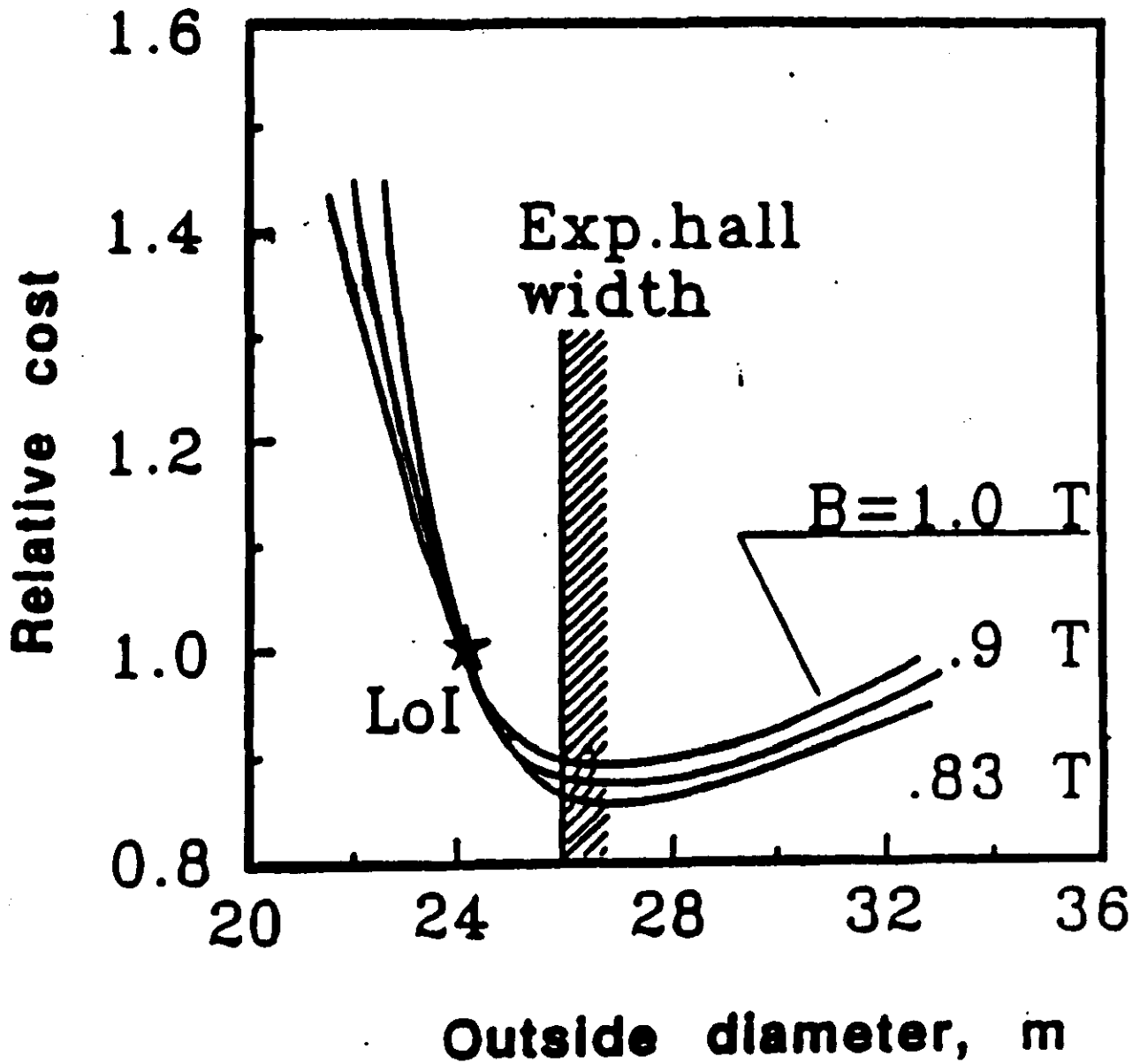
$L = 4030$ mm = 7936 - 3906

Use An Automated Wire Pulling Machine to:

1) Position Wires In Chamber
2) Tension Them
3) Solder Them
4) Check Tension & Position & Log into a Computer Database



From the L* LOI.....



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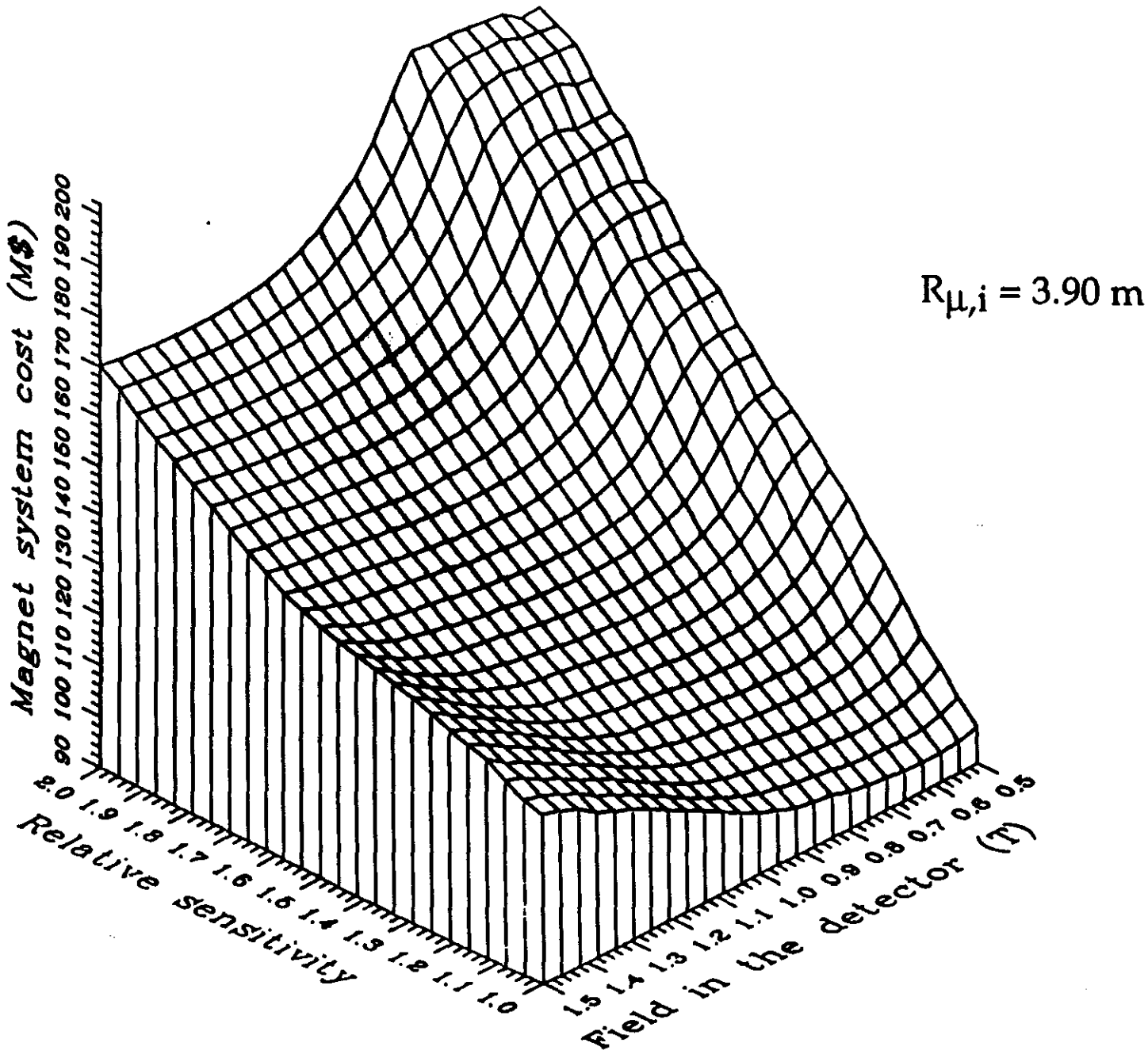
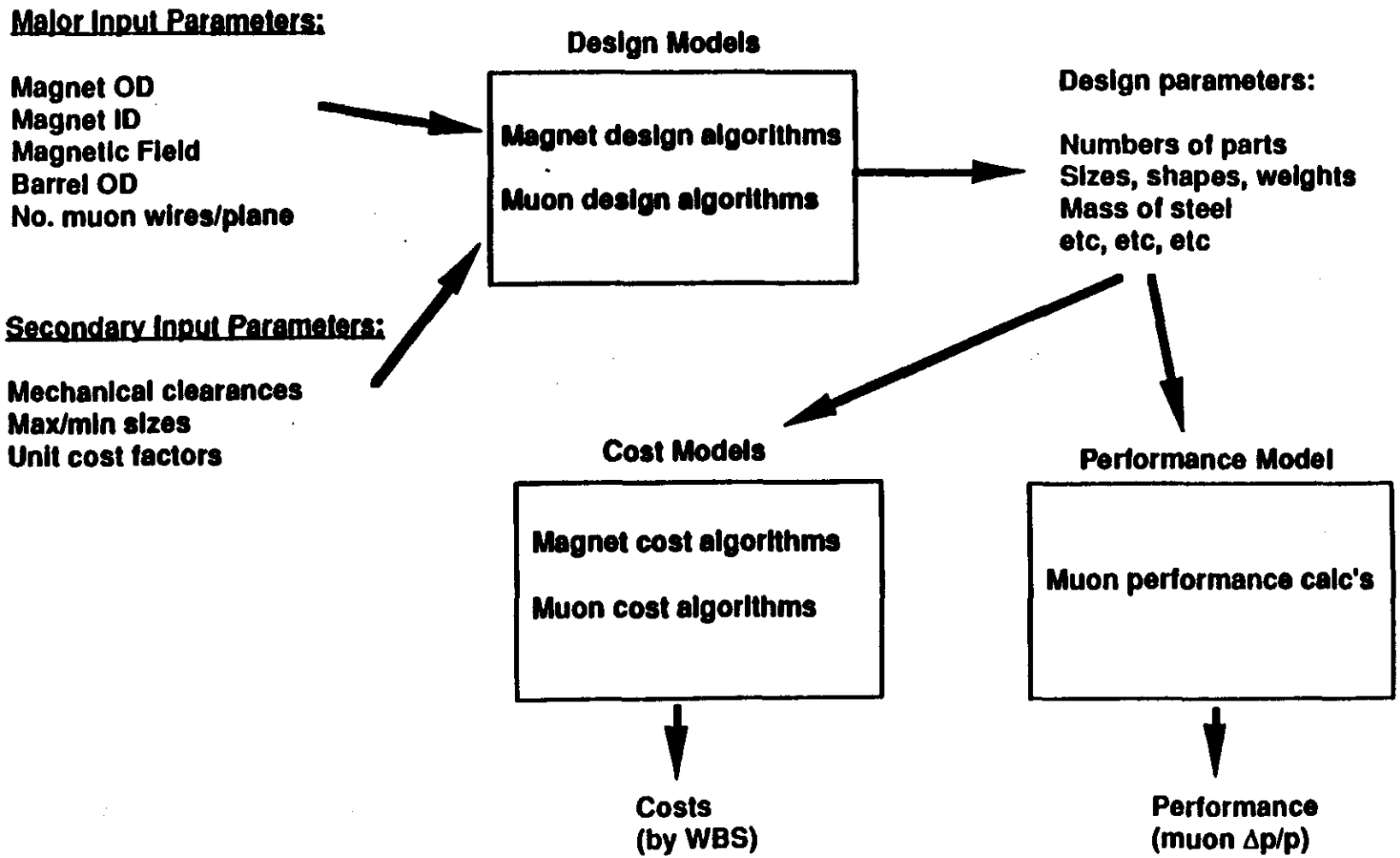
8/6/91

Cost vs field and sensitivity relative to 10 T·m2



$R_{\mu,i} = 3.90$ m

LLNL's parametric cost model permits overall system optimizations

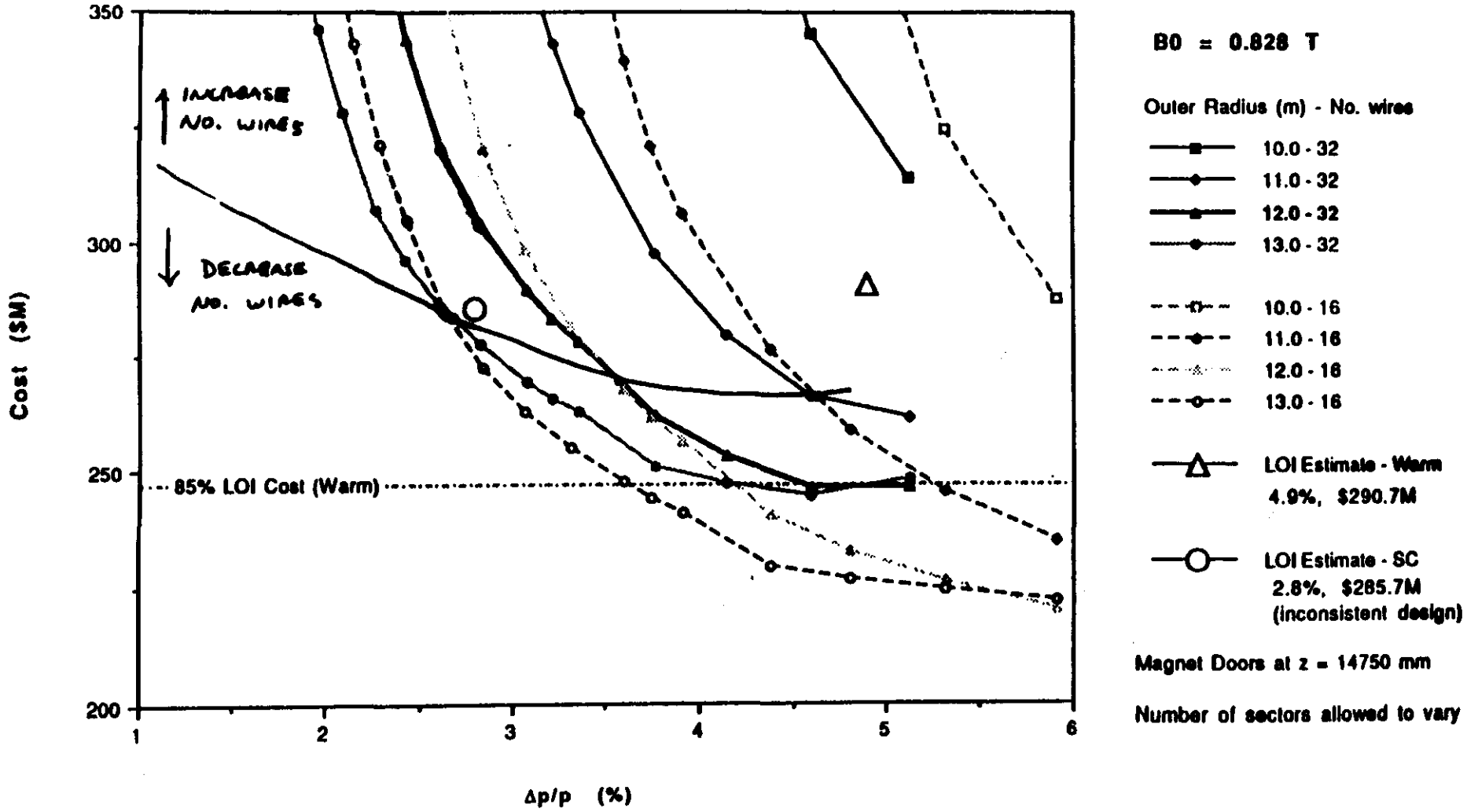


gdt.DRD92-8
8/6/91

Muon/SC Magnet Cost Model - V1a

Cost vs Performance at B0 = 0.828T

Data from "CvsP/.828T/16,24,32/data"



CvsP/.828T/16&32
gd-3/26/91-1025

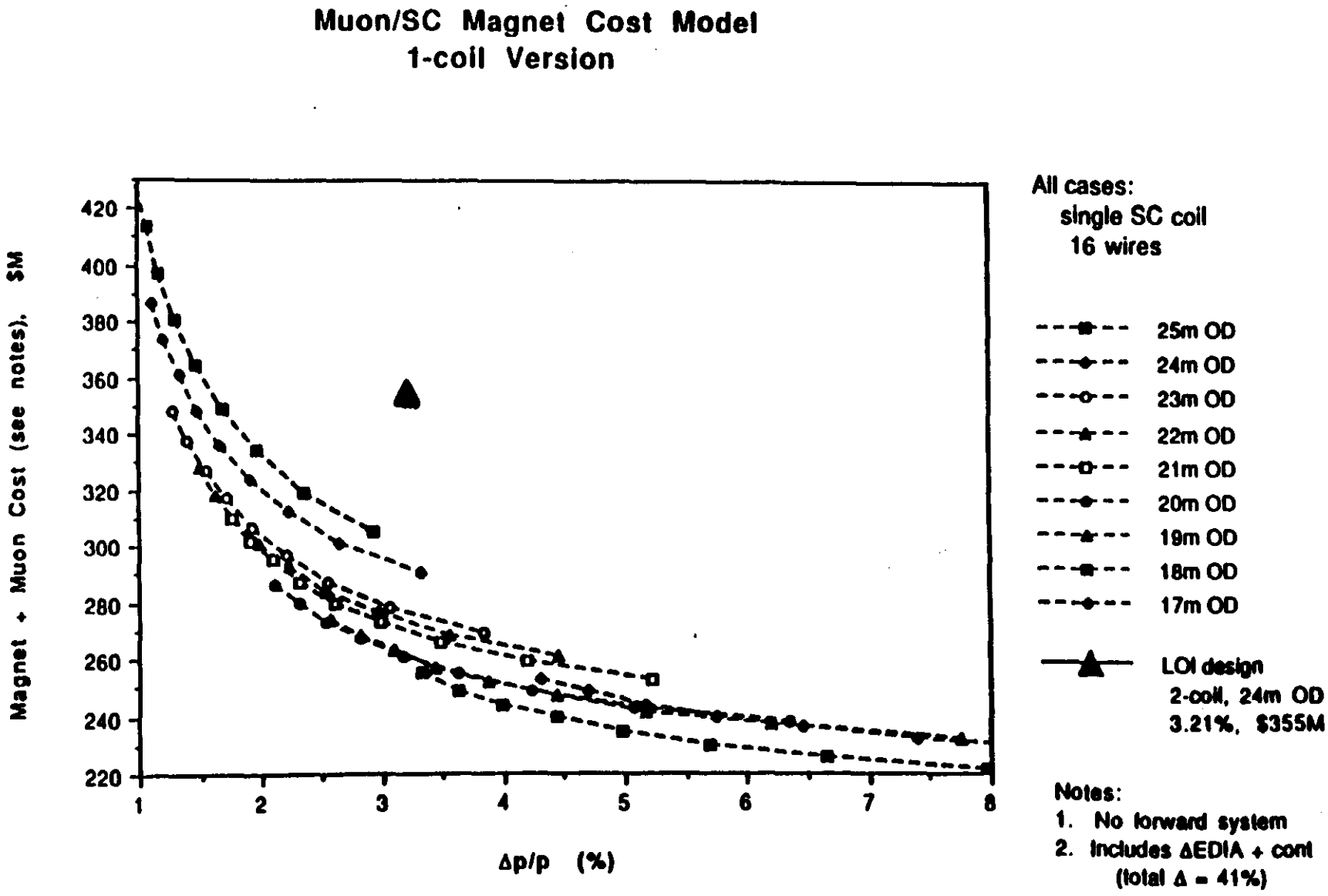
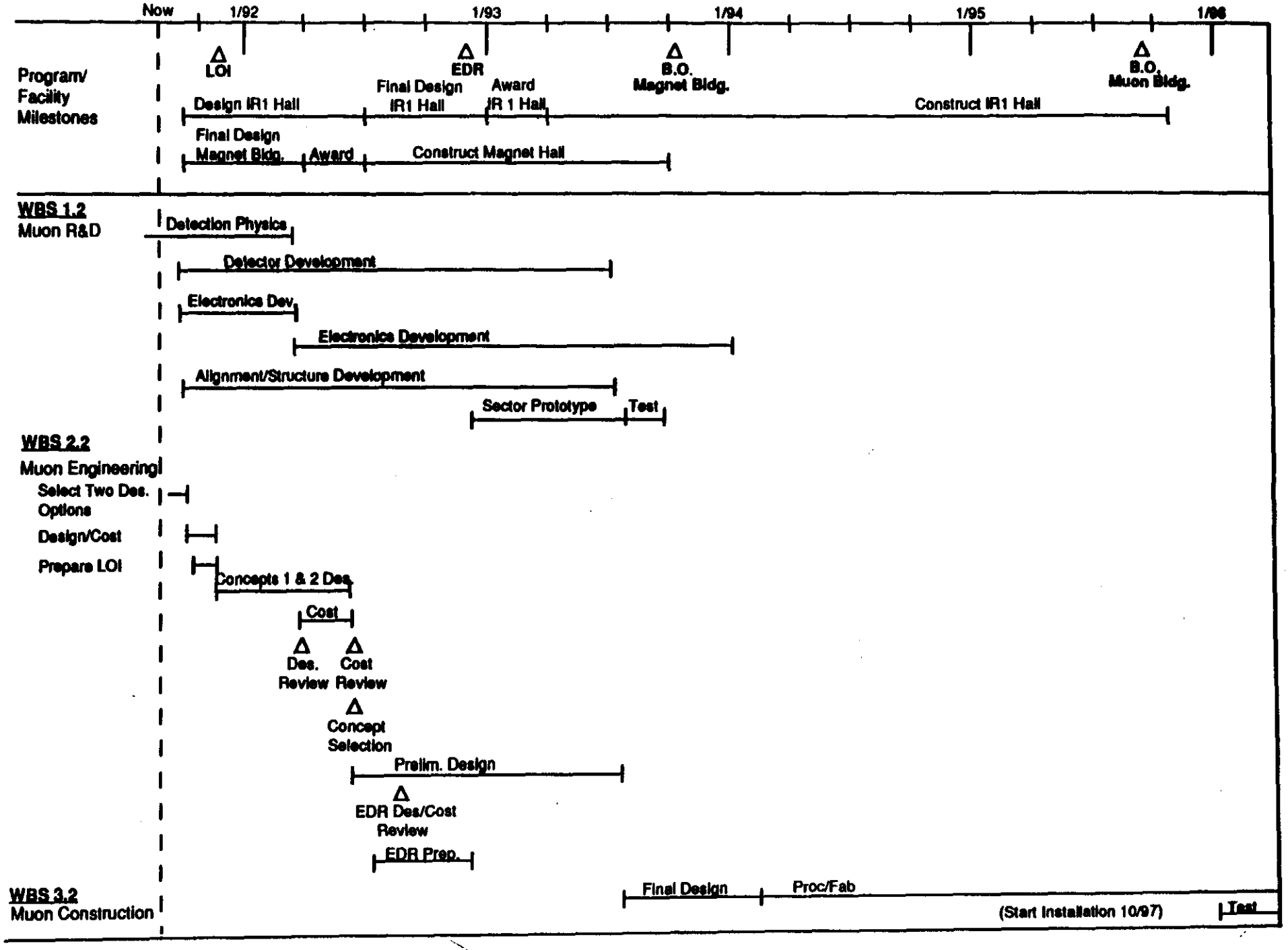


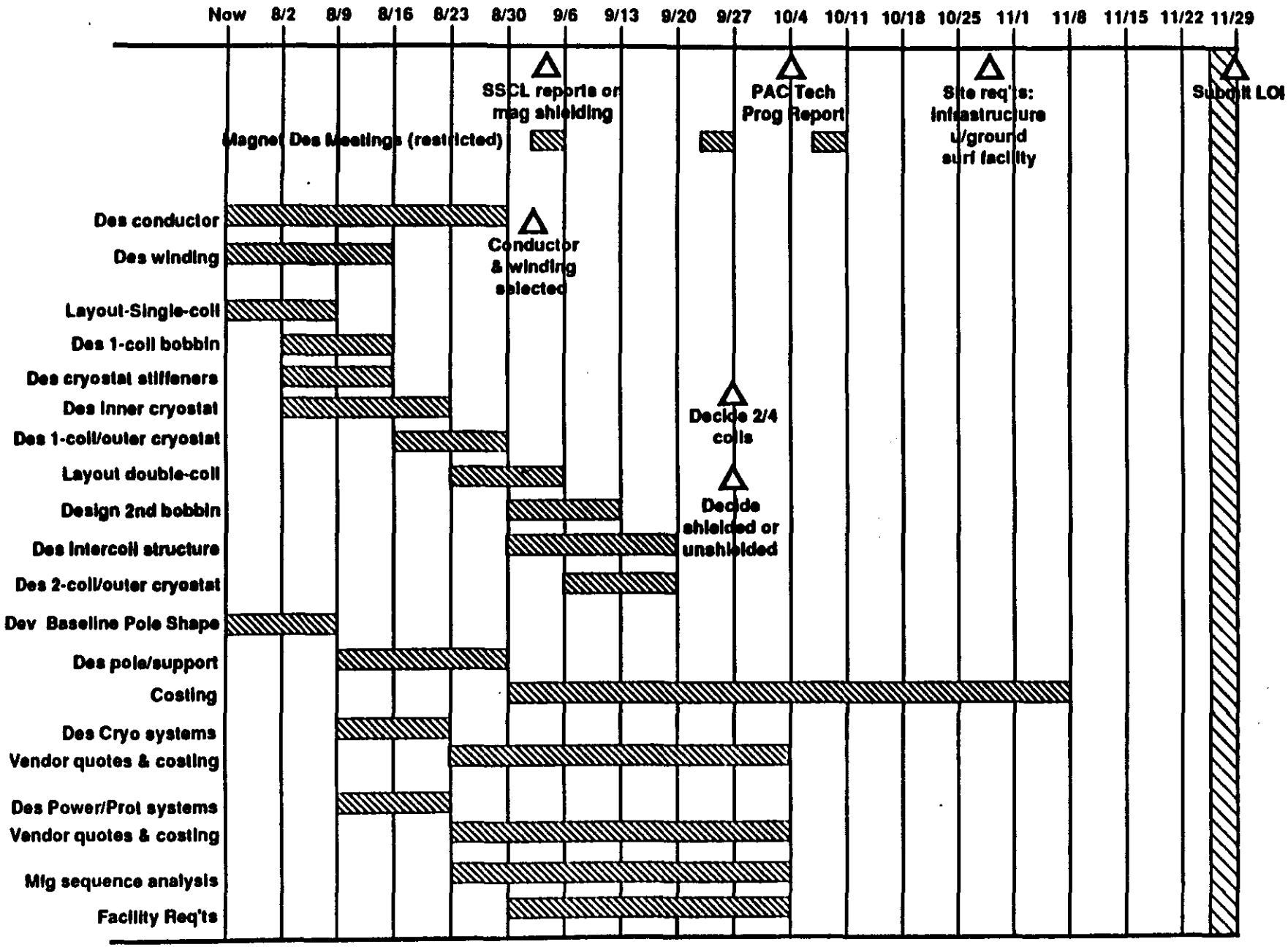
Figure 5-3 Parametric cost plot for the single coil magnet option.

MUON ENGINEERING AND R&D SCHEDULE

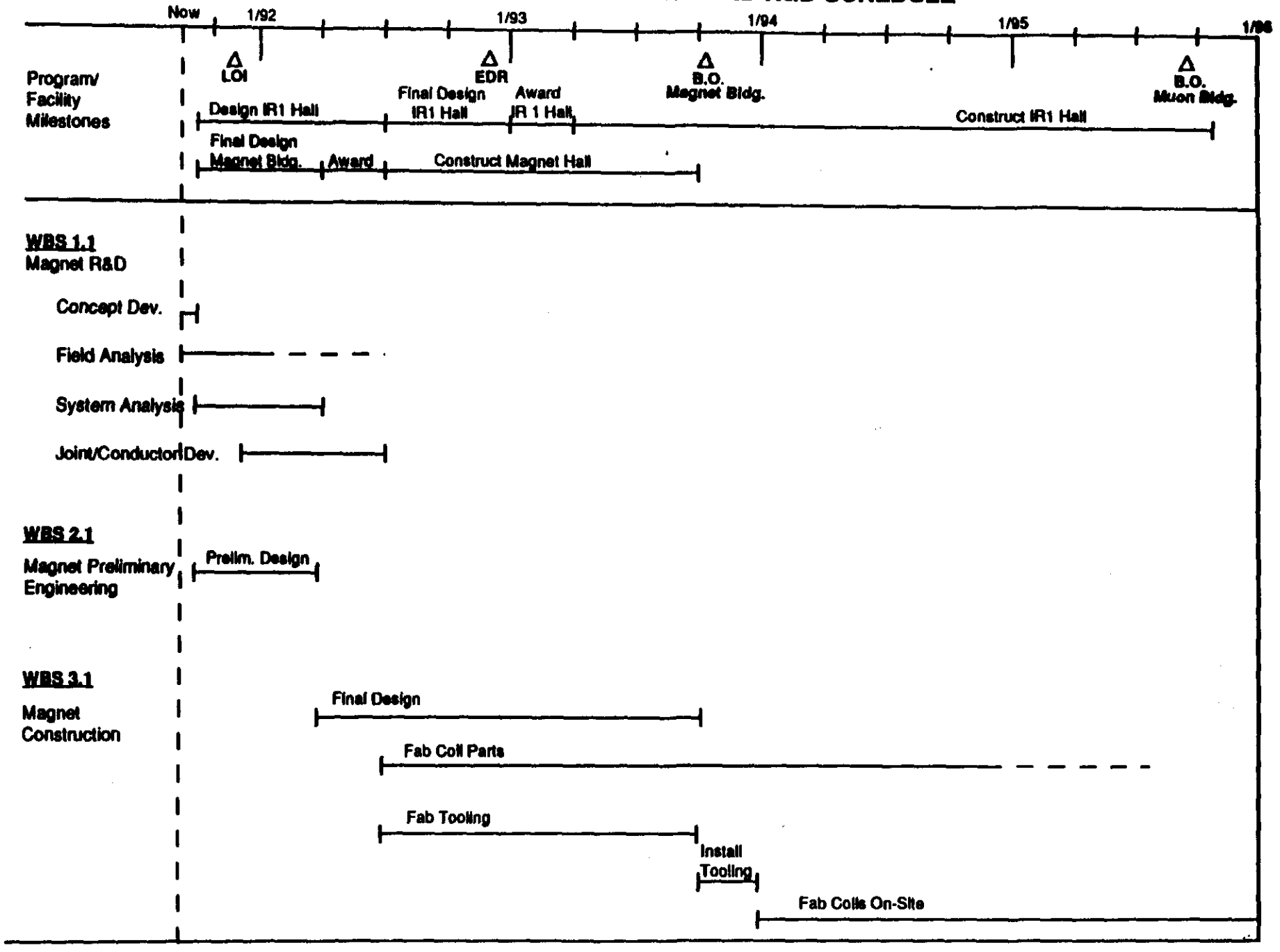


GEM Magnet Near-Term Schedule

DRAFT 7/31/91 - 1414



MAGNET ENGINEERING AND R&D SCHEDULE



R & D Issues

a) Determine Best Gas

b) Monte Carlo Study of how to gang Sense Wires

c) Complete R&D on an Automated Wire Pulling & Characterization System

d) Develope a Resistive Wire Readout for One Sense Wire per plane

e) Improve Alignment Techniques
→ more bridges enabling $\frac{1}{2}$ magnet length Chambers

f) Determine Endcap Chamber Configuration

g) Determine Chamber Support Structure and Stability Criteria

Talk by Bob Miller on
Straw Tube Option

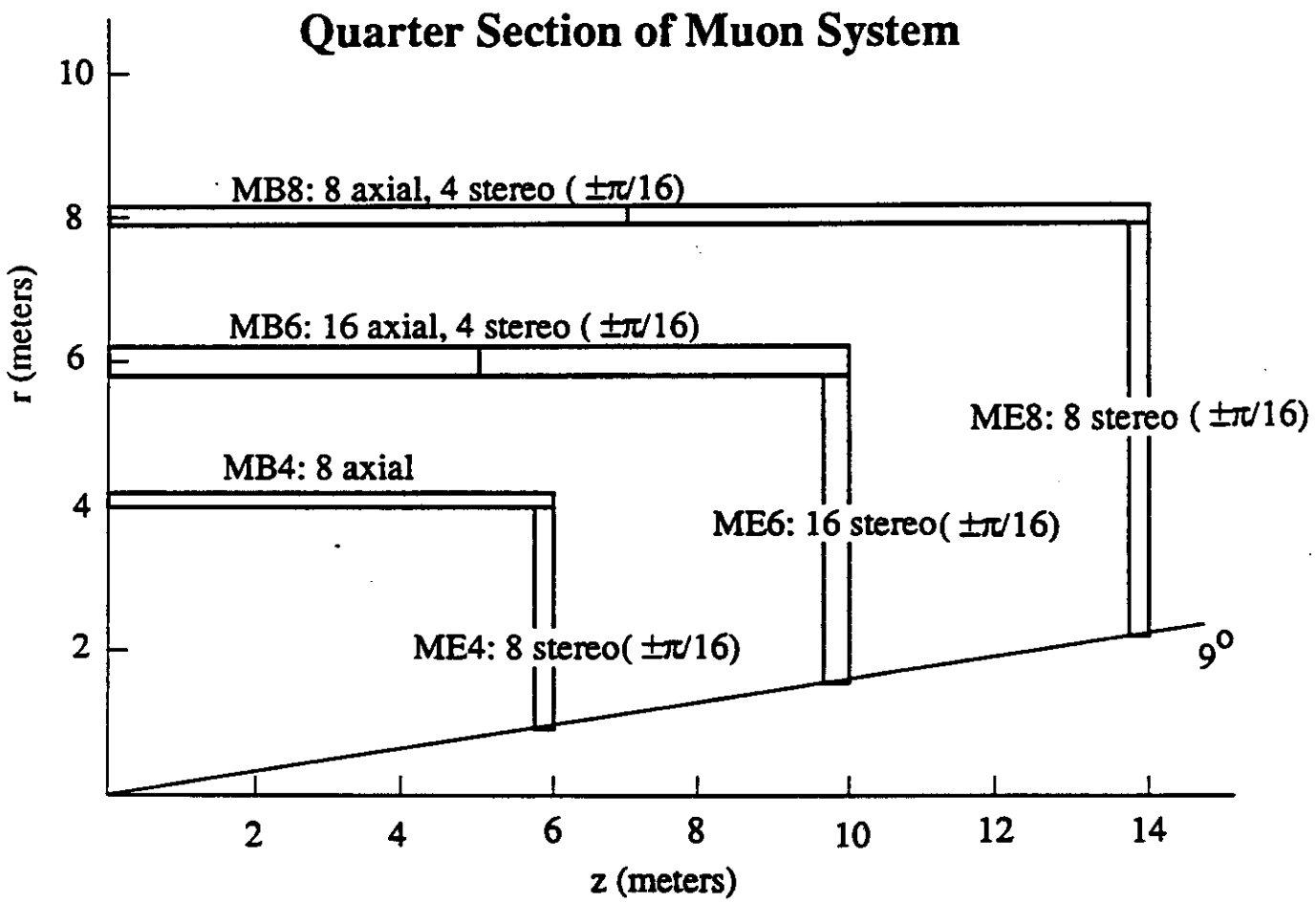
A GEM MUON SYSTEM

BASED ON 2 cm Dia. STRAW DRIFT TUBES

C. Bromberg, R. Miller, B. Pope, C. Yosef

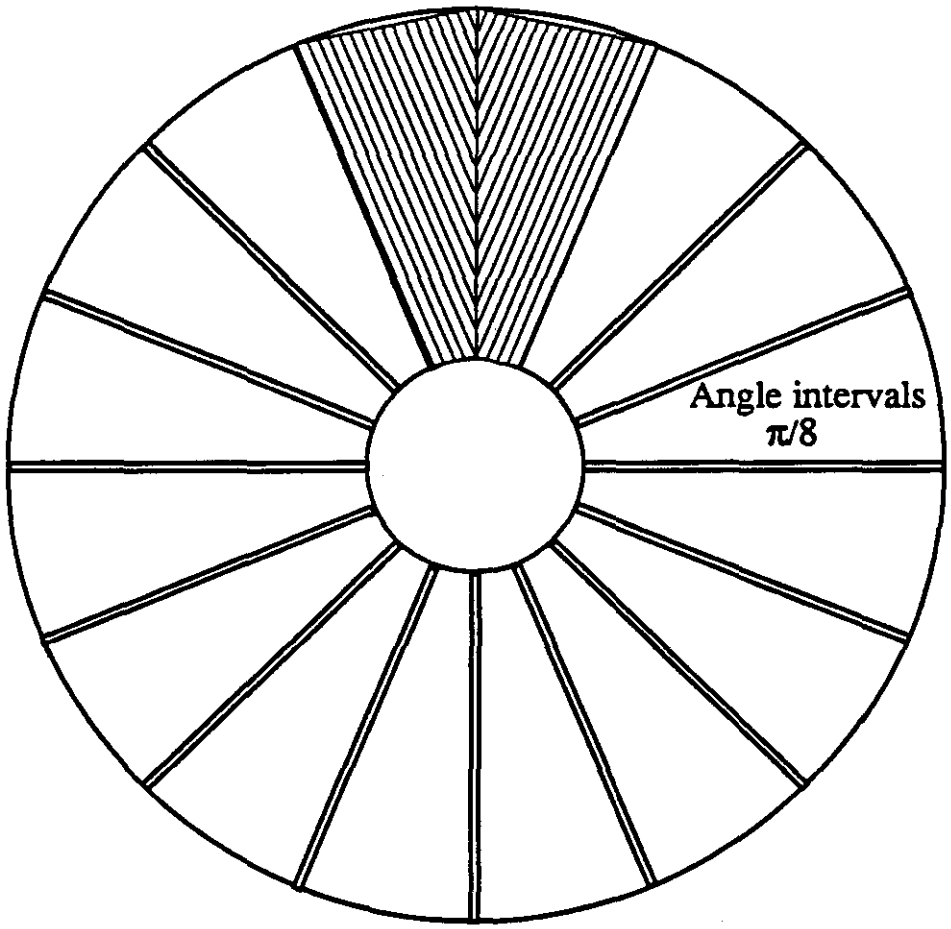
Michigan State University

Potential Advantages of Plastic Straws:
- Cost
- Ease of Construction
- Robust (vs planar cathode)
- Pressure > 1 atm (vs planar cathode)
- Radiation Length (vs. SS Tubes)
- Use in trigger

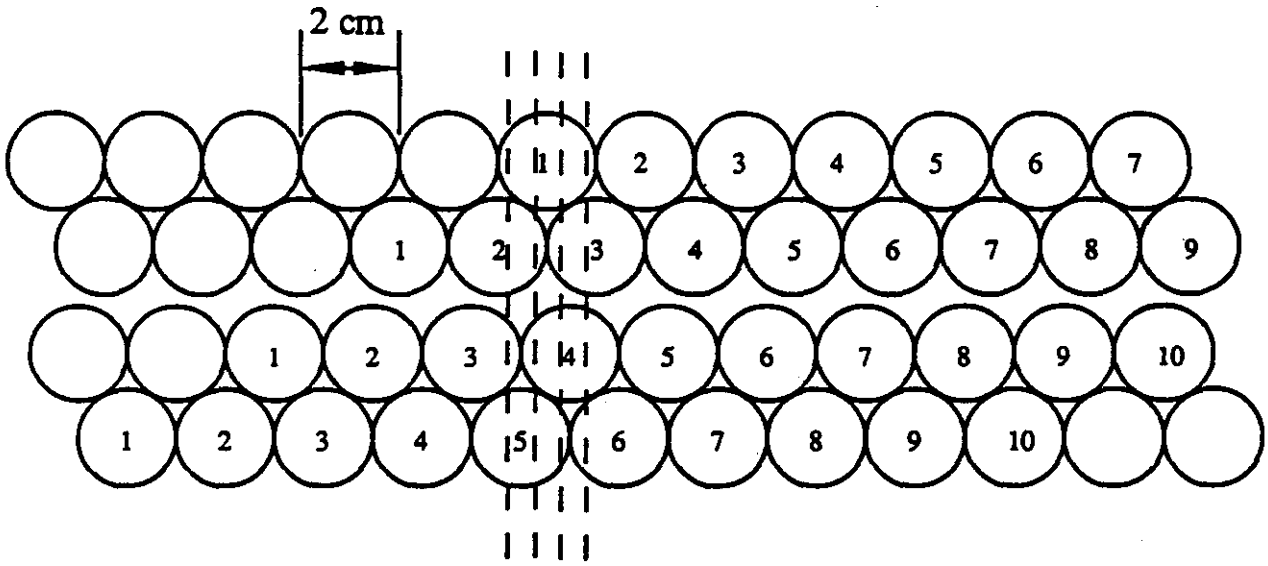

Quarter Section of Muon System
MB8: 8 axial, 4 stereo (±π/16)
MB6: 16 axial, 4 stereo (±π/16)
MB4: 8 axial
ME8: 8 stereo (±π/16)
ME6: 16 stereo(±π/16)
ME4: 8 stereo(±π/16)
9°
r (meters)
z (meters)
10
8
6
4
2
2
4
6
8
10
12
14

END CHAMBER STEREO

Layers alternate between styles shown



Gangs of Four



TRIGGER LOGIC:

location: 1·2·3·5, 1·2·4·5, 1·3·4·5, 1·3·4·6, 2·3·4·6, 2·3·5·6, etc.

timing: 1+2+3+5, 1+2+4+5, 1+3+4+5, 1+3+4+6, 2+3+4+6, 2+3+5+6, etc.

GEM- STRAW TUBE DRIFT CHAMBERS

BARREL CHAMBERS:

Station	Radius	Length	Layers	#/Layer	Tubes	M'plex	Amp/disc
MB4	4.00	6.00	8 axial	1256	20096	2	10048
MB6	6.00	2 x 5.00	16 axial	1885	60320	4	15080
	6.00	2 x 5.00	4 stereo	1885	15080	4	3770
MB8	8.00	2 x 7.00	8 axial	2512	40192	4	10048
	8.00	2 x 7.00	4 stereo	2512	20192	4	5024
Totals			40		155880		43970

END CHAMBERS:

Station	Z	Max. R	Layers	#/Layer	Tubes	M'plex	Amp/disc
ME4	6.00	4.00	8 stereo	16 x 76	19456	2	9728
ME6	10.00	6.00	16 stereo	16 x 114	58368	4	14592
Me8	14.00	8.00	8 stereo	16 x 153	39168	4	9792
Totals			32		116992		34112

GEM- STRAW TUBE CHAMBER COST

Item	Required (K)	Unit Cost ($)	Total ($M)
Straw Tubing (m)	2400	1	2.4
End plugs	820	1	0.8
End seals	820	1	0.8
Centering pins	820	2	1.6
Wire (m)	2400	0.5	1.2
Precision Holes	820	1	0.8
End Plates	2.5	1000	2.5
Amp/discrim.	78	10	0.8
TDC's (m'plex by 4)	19.5	100	2.0
PC boards, cables	5	100	0.5
Labor hrs.(10 min/tube, 2 techs)	134	50	6.7
Alignment Equip.	0.6	1000	0.0
Gas system/plumbing			0.5
Total			20.6

R & D Items

1. Test of High-pressure straw tube designs (end plug)
2. Test of positioning accuracy obtainable for these designs
3. Engineering studies to evaluate construction procedures, support structure and costs
4. Monte Carlo study of multiplexing scheme in a SSC environment, both for pattern recognition and triggering

Talk by Louis Osborne

on Limit Streamer Tubes

EMPACT Note 358
Dec. 3, 1990
Ammended,
Feb. 20, 1991

STUDIES OF DRIFT AND STRIP READOUTS FOR THE EMPACT/TEXAS MUON SYSTEM

(preliminary results)

Yu. Bonyushkin, N. Khovansky, A. Korytov, V. Malyshev, Yu. Sedykh, V. Tokmenin

Joint Institute for Nuclear Research

Dubna, U.S.S.R.

Delphi Group

H. W. Kendall, L. S. Osborne, G. D. Ross, A. Sodickson, R. Verdier

Massachusetts Institute of Technology

Laboratory for Nuclear Science

Cambridge, Massachusetts

(SLD - VXIC)

Abstract

We report on the most recent results measuring the behaviour of wire chambers which might be suitable for EMPACT muon detectors. This includes several measuring techniques, chambers, and gasses.

1. Introduction

This study was initiated to find a particle measuring technique with gas detectors that would be suitable for the EMPACT muon detector system. It would have to be :

1) fast, ~~to tag events at~~ their proper collision time;*

2) accurate, $\sigma \simeq 200\mu m.$, but locatable to $50\mu m.$;

3) ammenable to mass production;

4) using non-flammable gas.

Limited Streamers in Drift Mode

Fast rise time ~ 10 nsec

Large pulses ~ 100 mv.

Hopefully:

Cheap

Mass producible

REFERENCES

1. K. Fujii et al, NIM, A225, 23(1984)

2. F. Gasparini et al, NIM, A267, 87(1988)

The authors of these papers claim they did not achieve the best possible resolutions due to lack of mechanical alignment and multiple scattering.

Gases Considered

Argon(A), Isobutane(IB)
A(few %),IB(10 %), CO_2
A(few %),IB(10%),CO_2,CF_4

IB($\leq$10%)-non-flammable
CO_2-ohmic,slow,cool
CF_4-flat,fast

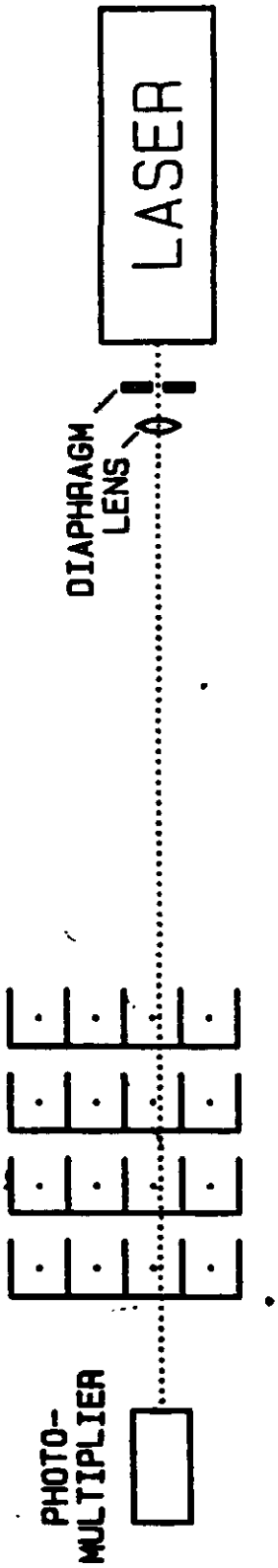


Fig. 2.1

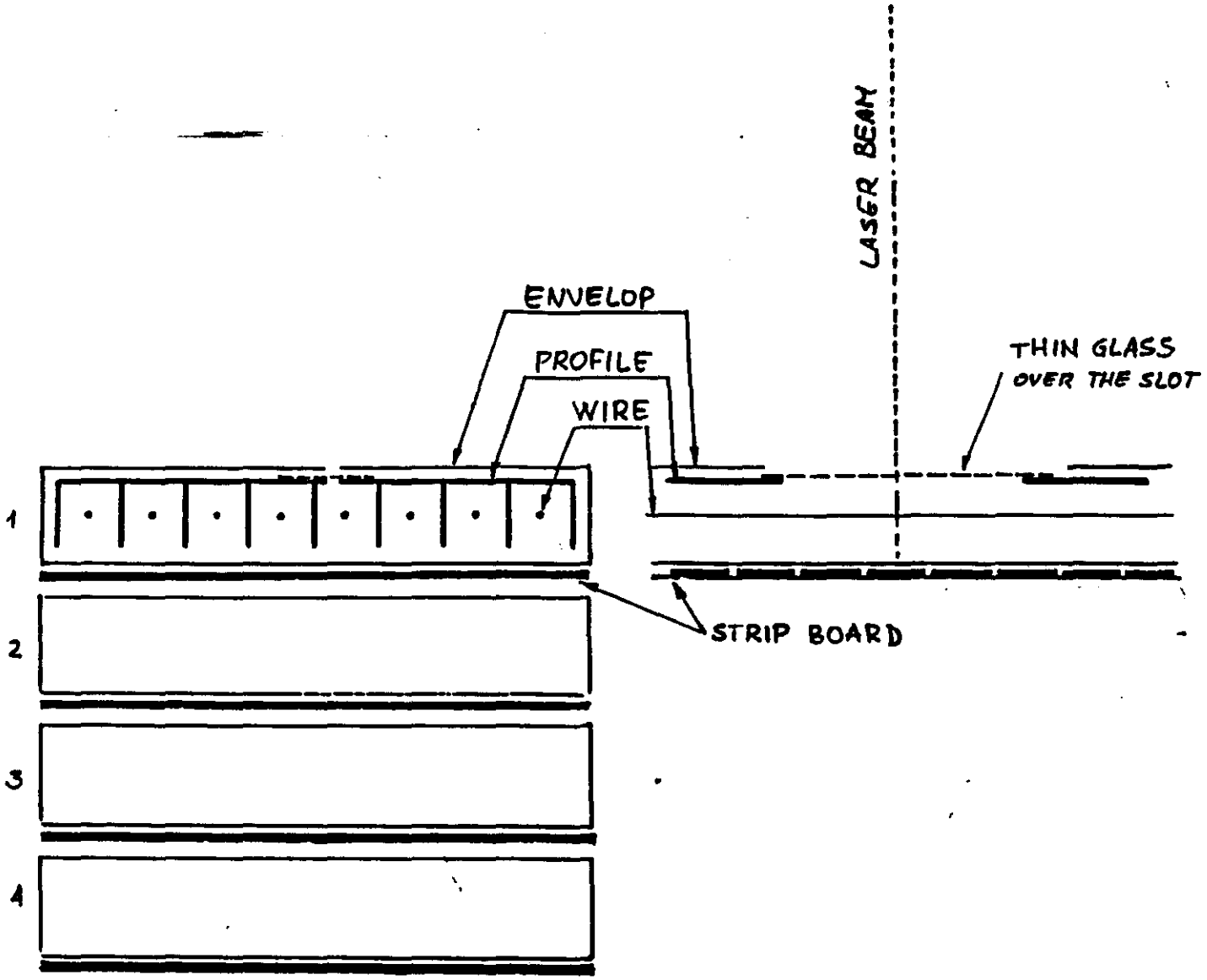

LASER BEAM
ENVELOP
PROFILE
WIRE
THIN GLASS
OVER THE SLOT
1
2
3
4
STRIP BOARD

Fig. 2.2

Argon-Isobutane (Laser)

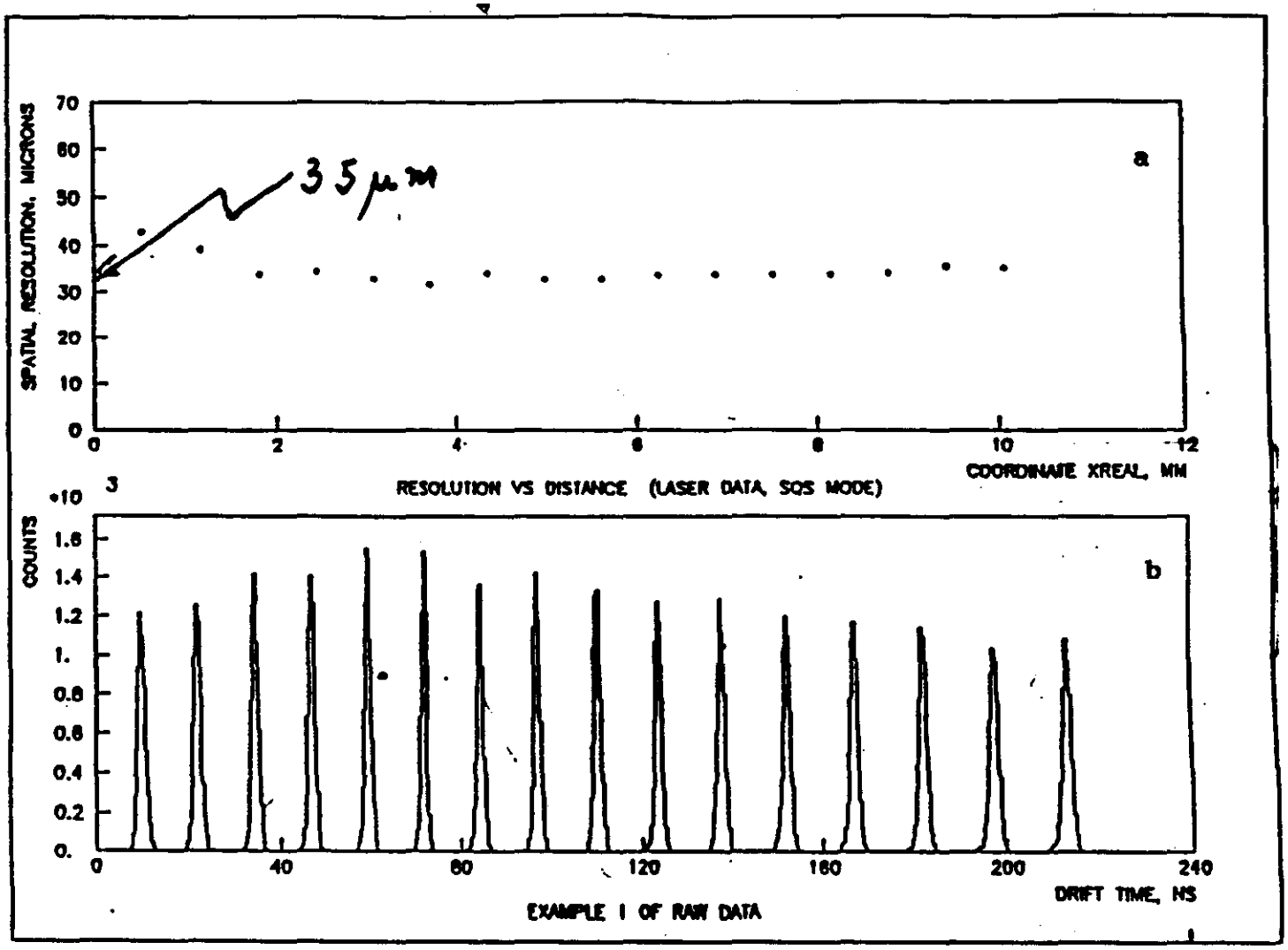


Fig. 3.2

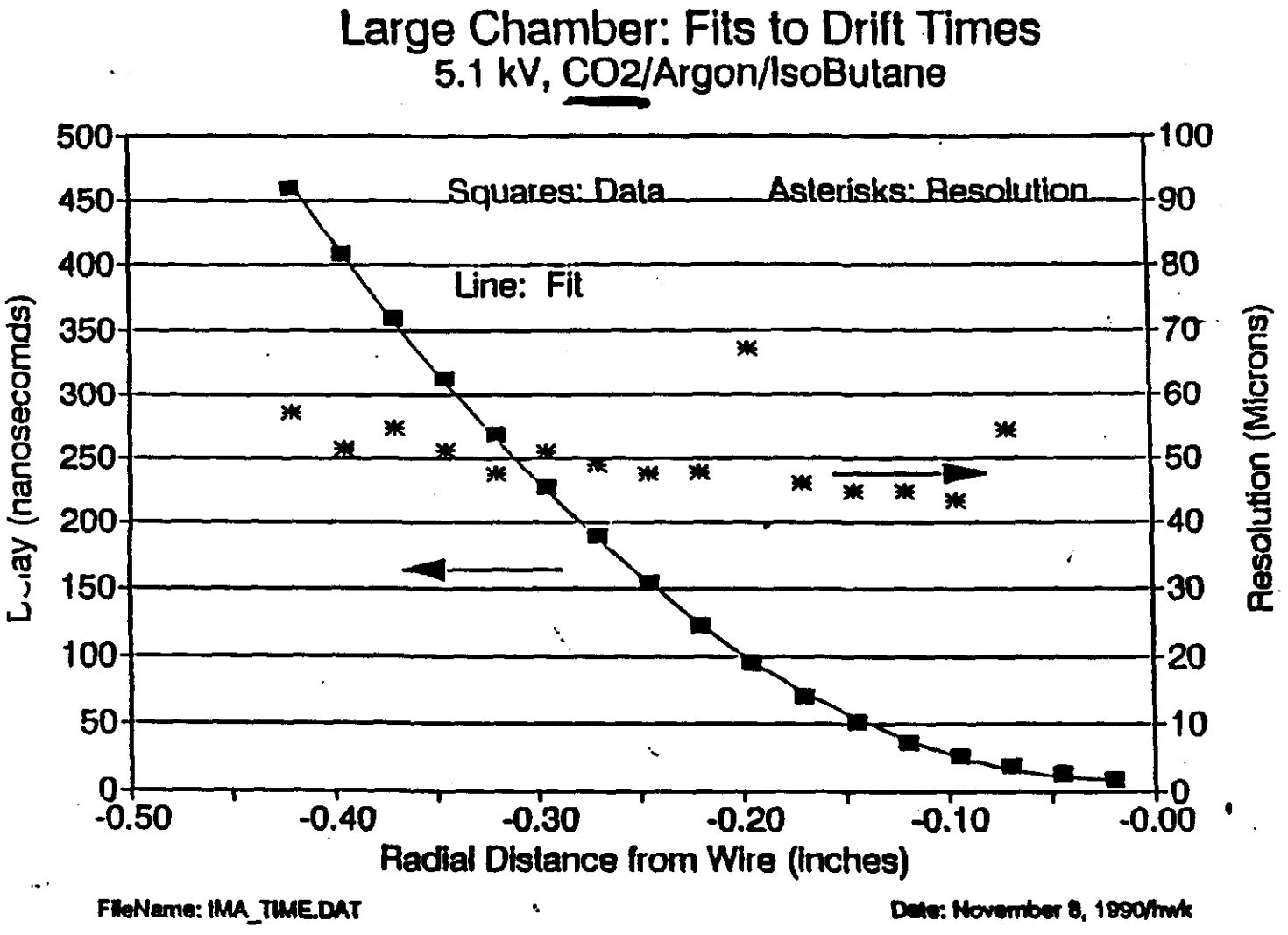

Large Chamber: Fits to Drift Times
5.1 kV, CO2/Argon/IsoButane
Squares: Data
Asterisks: Resolution
Line: Fit
Delay (nanoseconds)
Resolution (Microns)
Radial Distance from Wire (Inches)
500
450
400
350
300
250
200
150
100
50
0
100
90
80
70
60
50
40
30
20
10
0
-0.50
-0.40
-0.30
-0.20
-0.10
-0.00
FileName: IMA_TIME.DAT
Date: November 8, 1990/hwk

Fig. 3.3

$CF_4 + CO_2 + Isobutane$

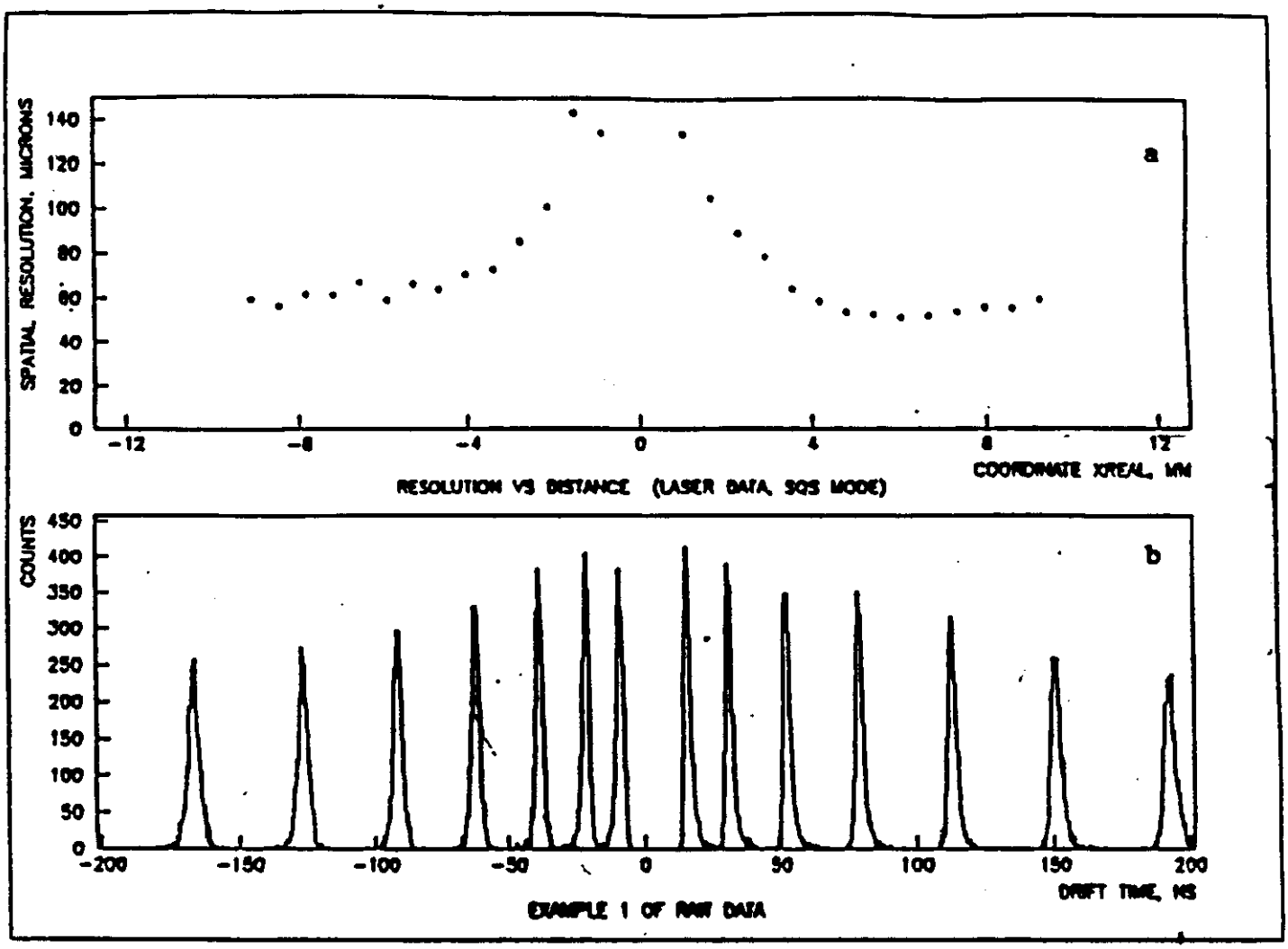


Fig. 3.6

Cosmic Rays - A + Isobutane

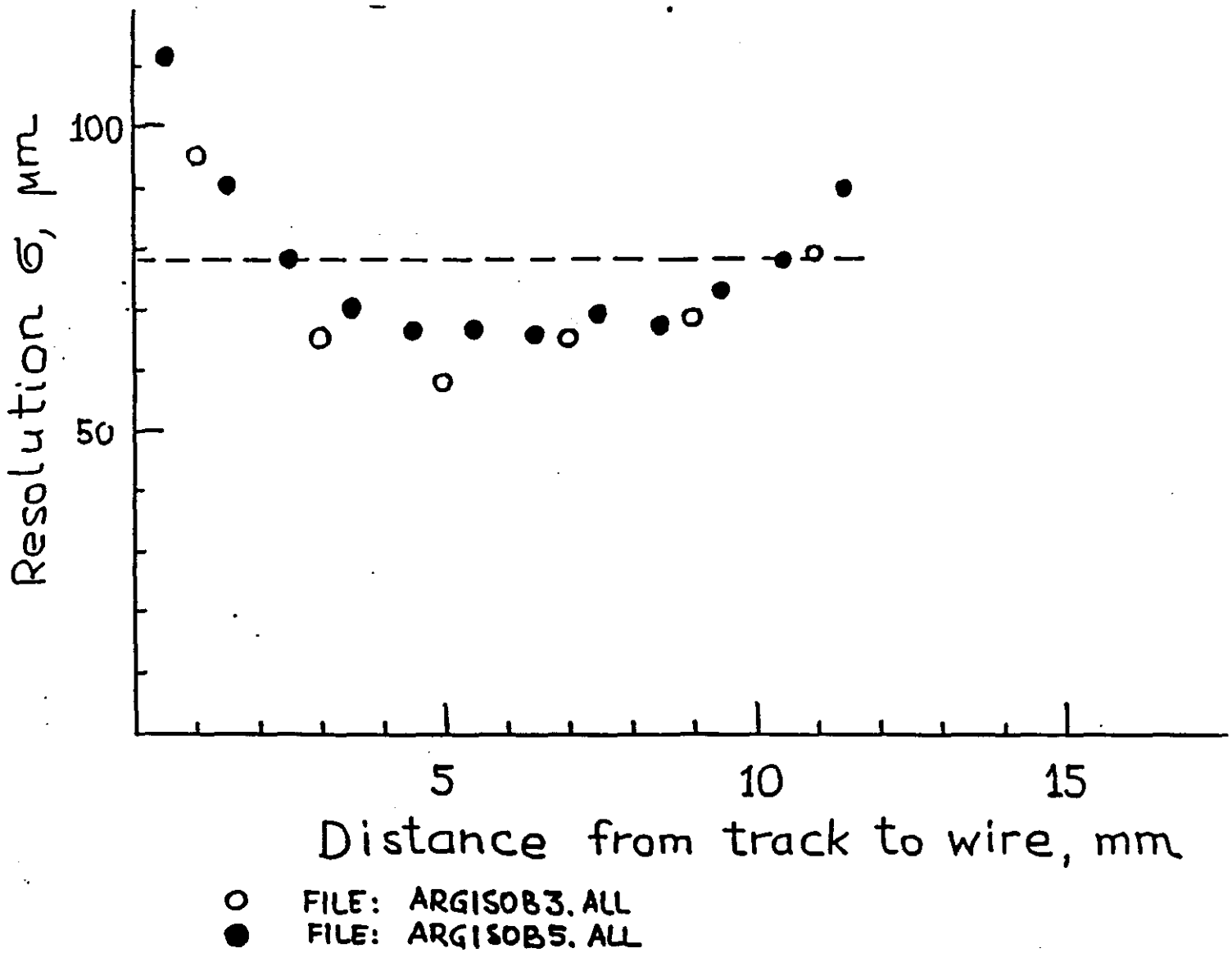


Fig. A.4

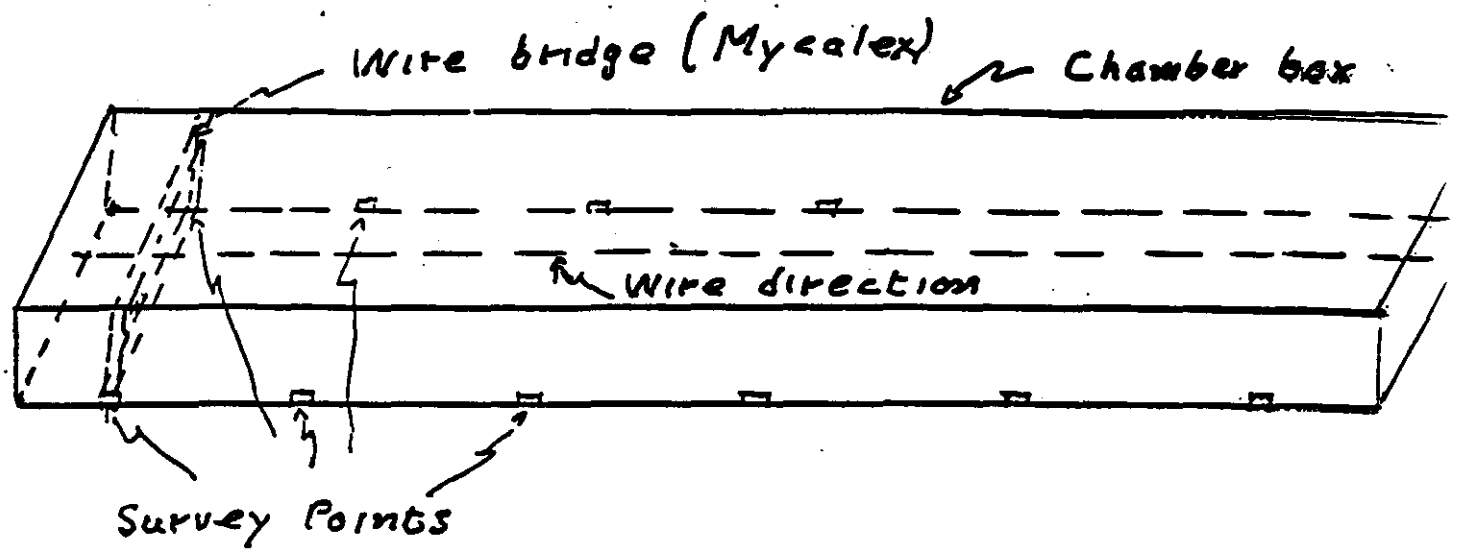
GEM Prototype Full Scale Chambers
3x(6 m. X 0.5 M.) chambers

R and D Group

Dubna- Design and Test
Houston- Wire Placement Techniques
LeCroy- Timing Electronics
Houston- Simulation,Data Analysis
MIT- Design, Construction, Tests

Schedule:

Design- Spring '91
Parts Ordered- Summer '91
Assembly- Fall '91
Tests- Winter '91-'92



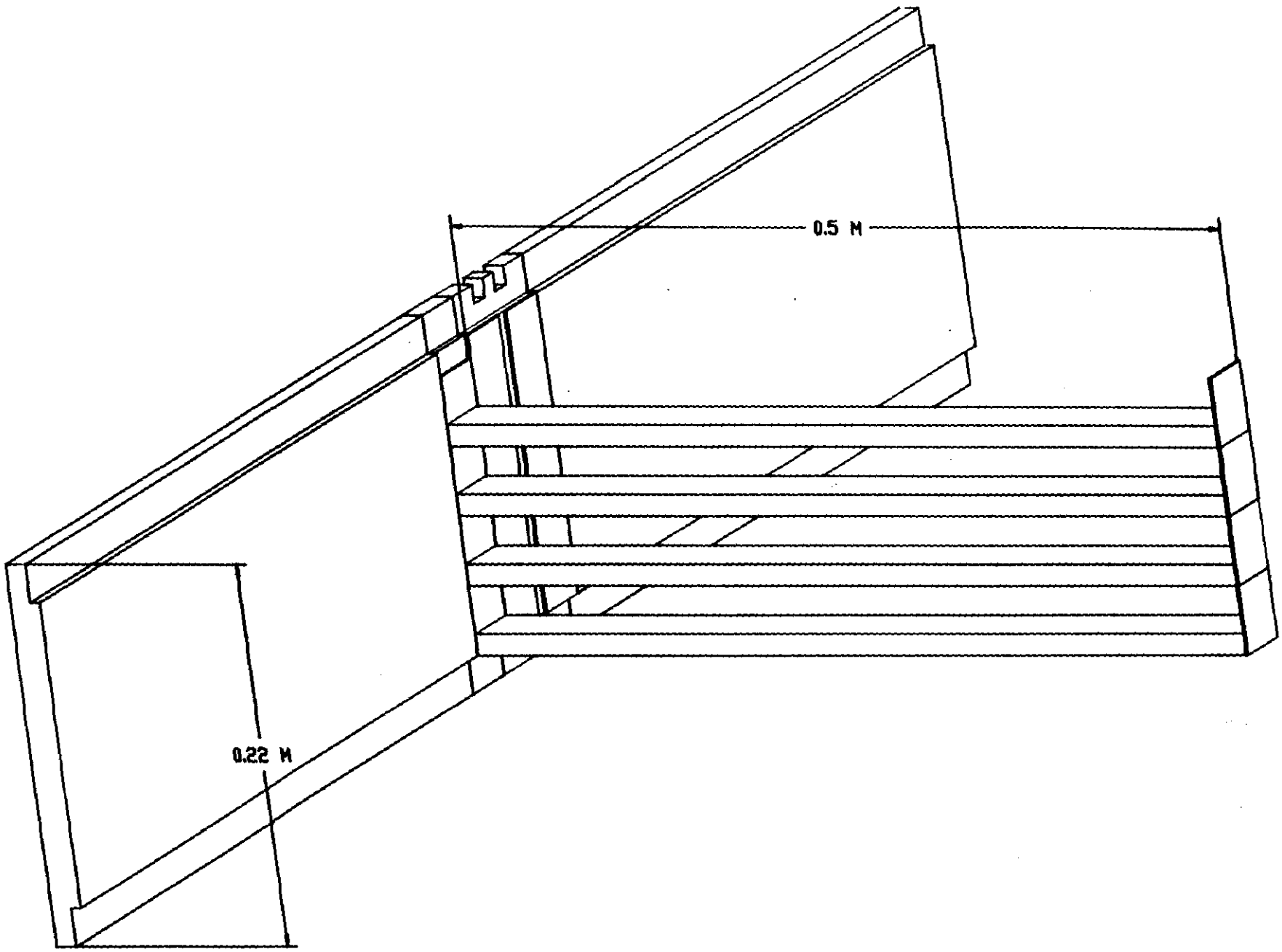
Philosophy

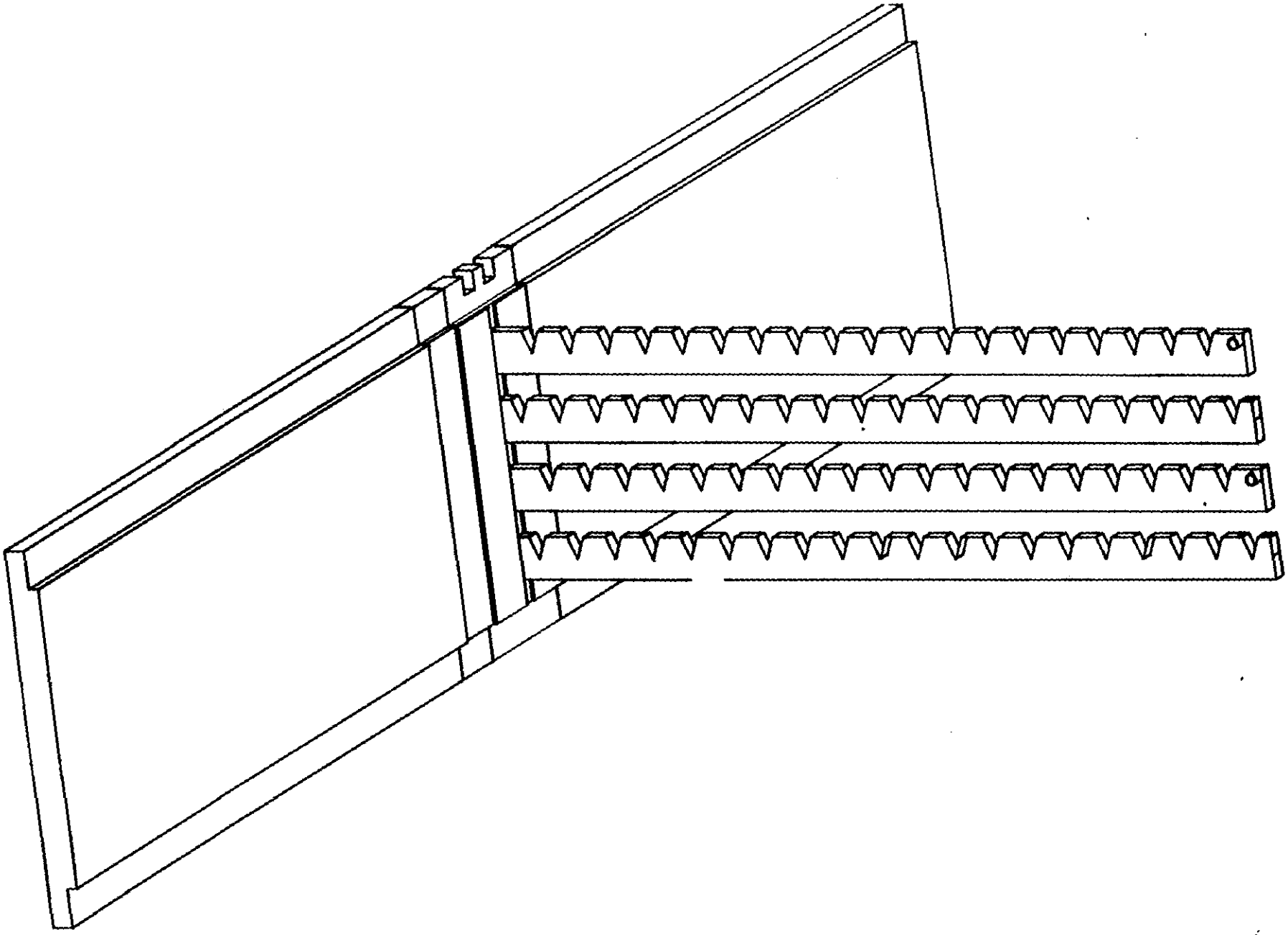
Wires placed to $\pm 12.5 \mu m.$ with respect to survey points,

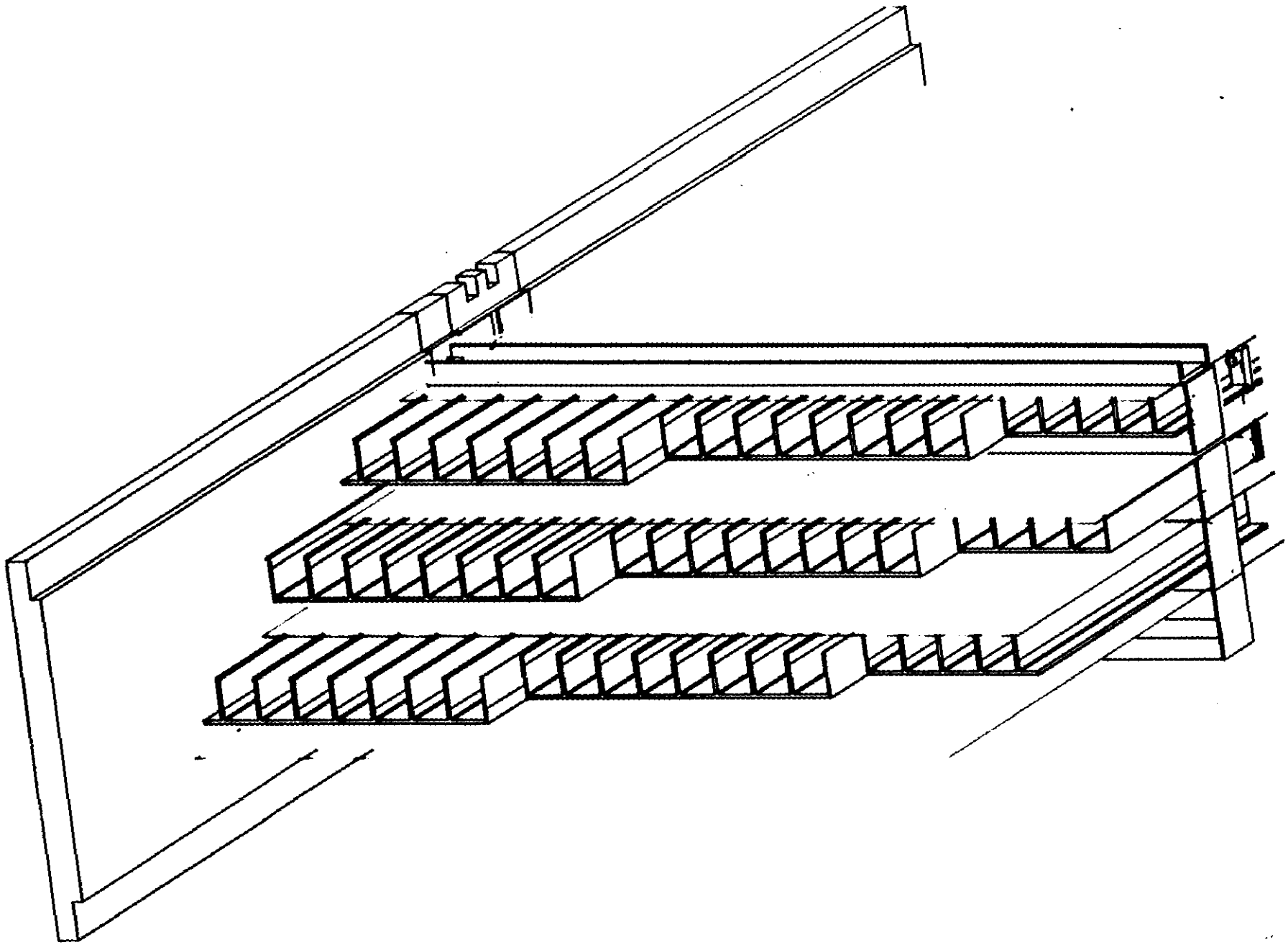
1) indenpendent of gravity
2) " temperature
3) " warp and sag of the chamber.

Survey points known to $\pm 12.5 \mu m.$,

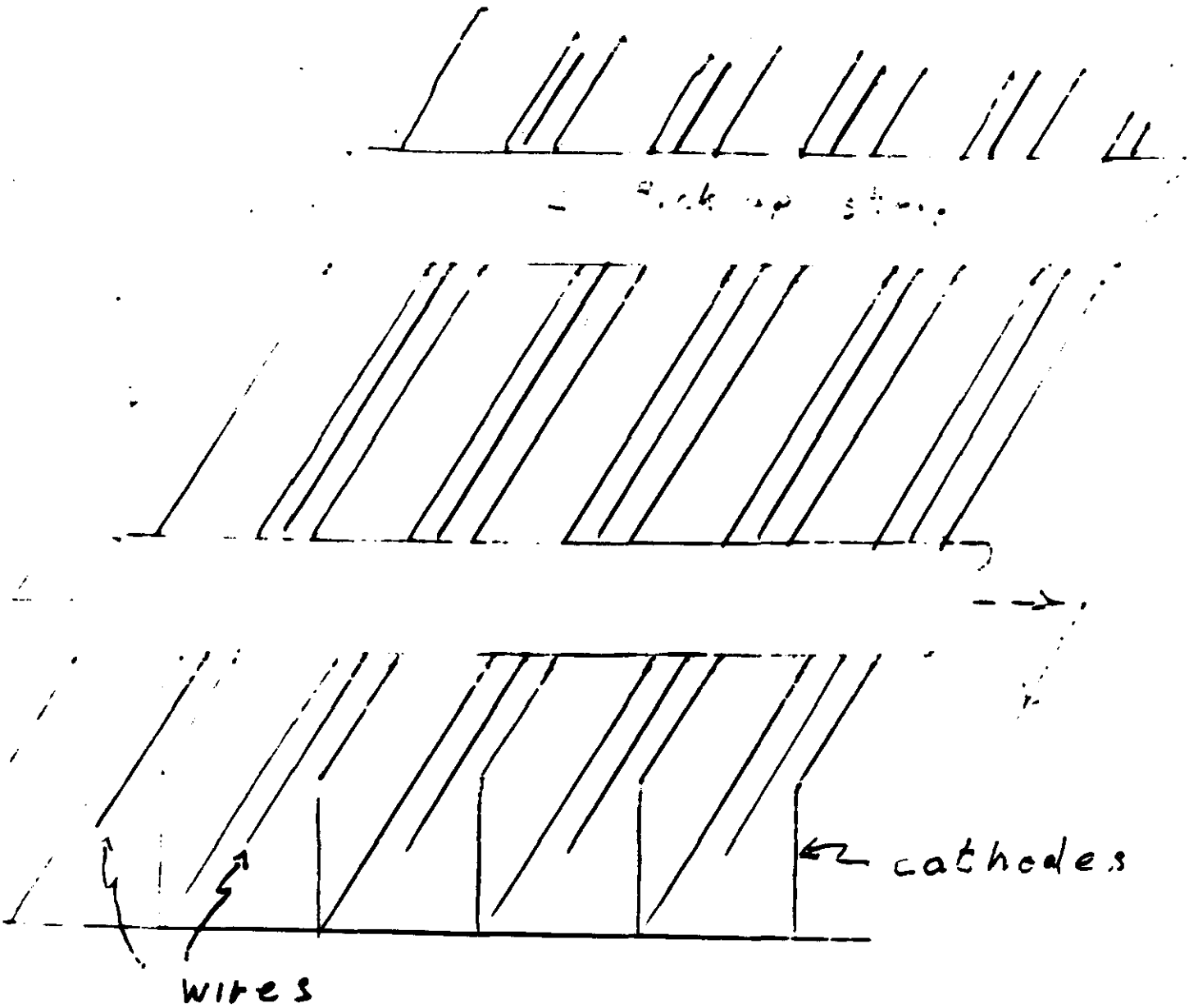
1)by surveying
2)by placement (unlikely)
3)by monitoring.


0.5 M
0.22 M

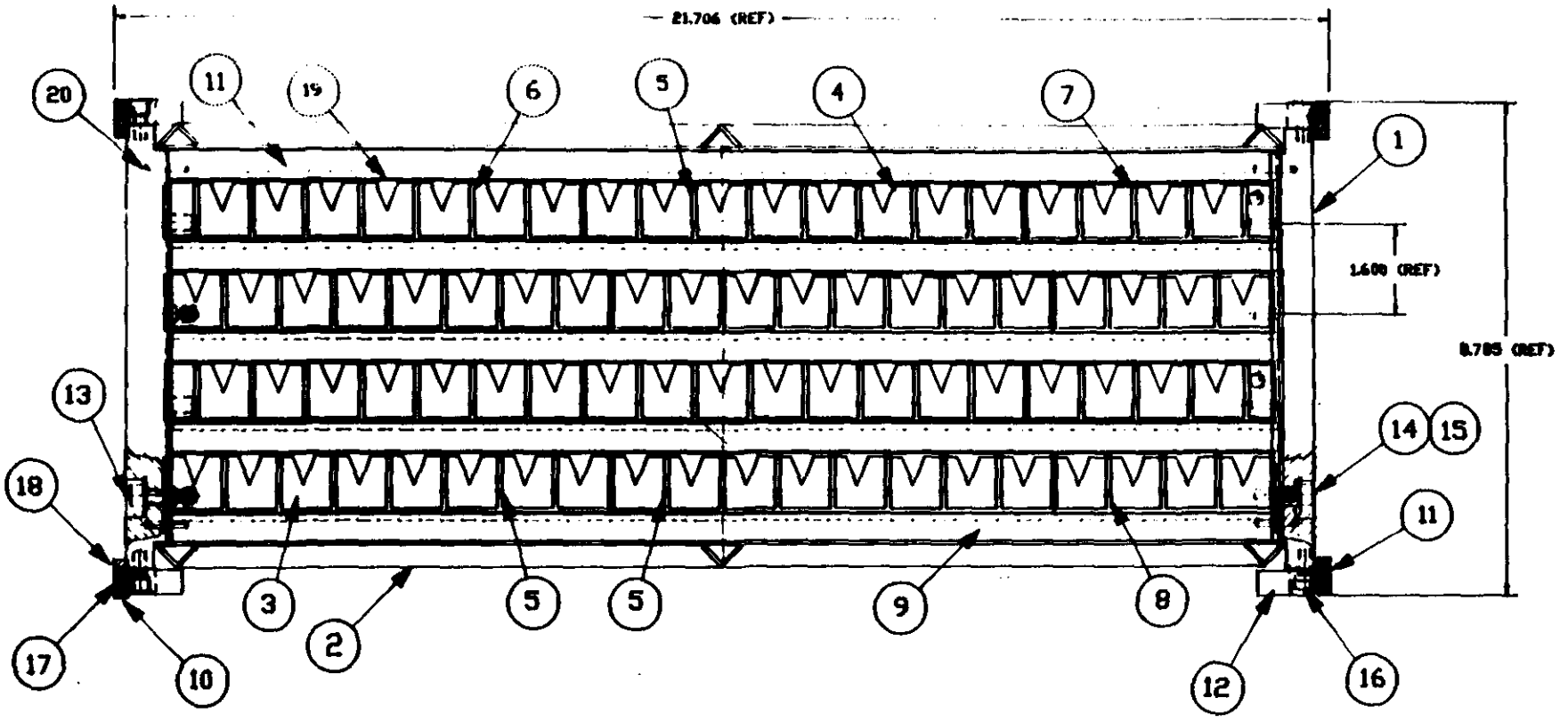




Z Measurement with Pickup Strips



Pickup strips make a vernier z-measurement within the timing measurement along the wire.
Several strips which bridge the accuracy of the timing measurement can be ganged in series.



		40	[illegible]
	[illegible]	4	[illegible]
	[illegible]	24	[illegible]
	[illegible]	8	[illegible]
	[illegible]	40	[illegible]
[illegible]		24	[illegible]
	[illegible]	24	[illegible]
[illegible]		20	[illegible]
	[illegible]	4	[illegible]
[illegible]		24	[illegible]
[illegible]		24	[illegible]
[illegible]		6	[illegible]
[illegible]		8	[illegible]
[illegible]		8	[illegible]
[illegible]		4	[illegible]
[illegible]		10	[illegible]
[illegible]		10	[illegible]
[illegible]		8	[illegible]
[illegible]		1	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]

REV	PCN	DATE	REVISION DESCRIPTION
C	LD	[illegible]	[illegible]
B	LD	[illegible]	[illegible]
A		[illegible]	[illegible]

LABORATORY FOR NUCLEAR SCIENC
MASSACHUSETTS INSTITUTE OF TECHNOL
CAMBRIDGE, MA 02139

PROTOTYPE MUON CHAMBE
PARTIAL SECTION
END VIEW

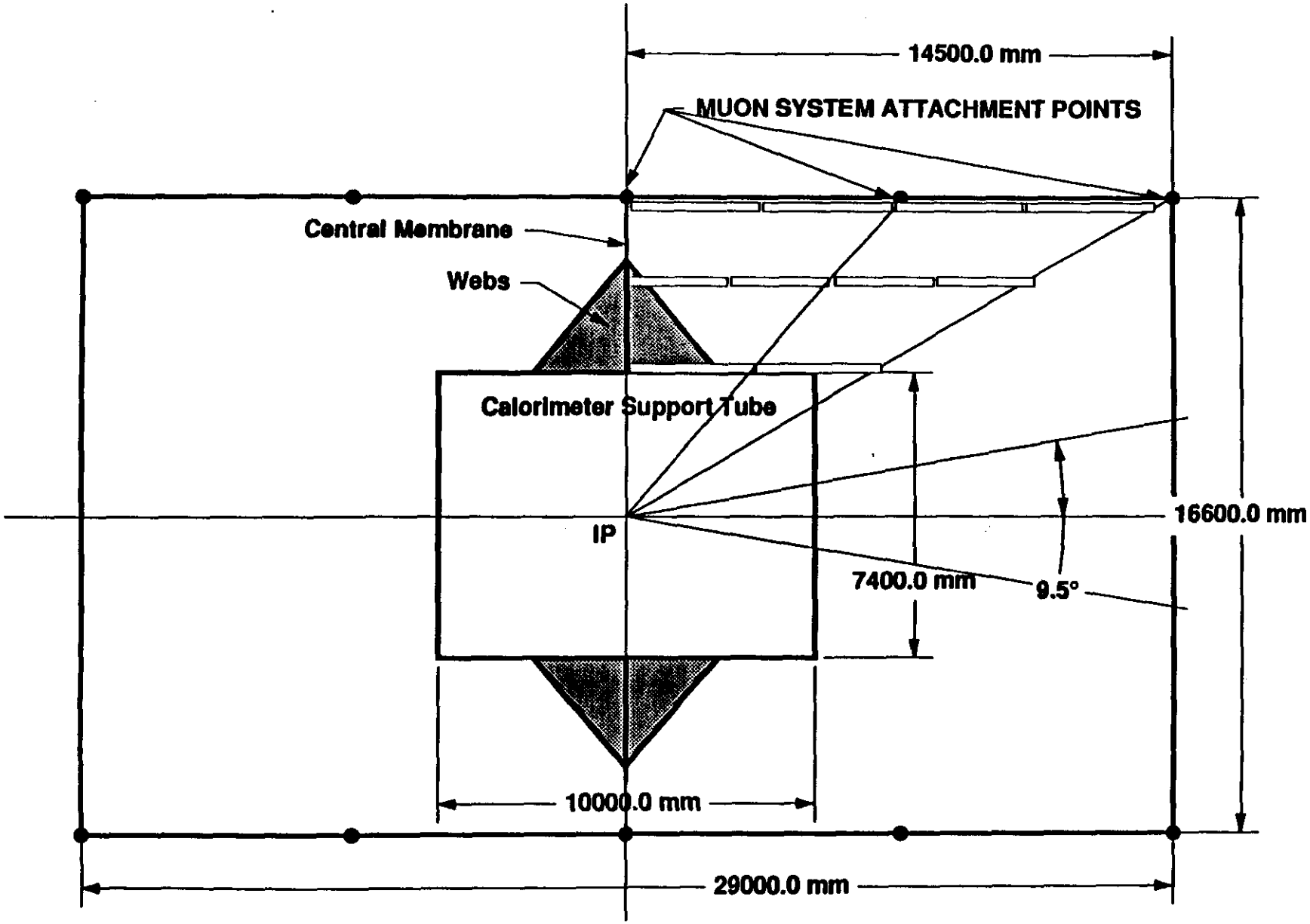
SCALE 1d

L S OSBORNE

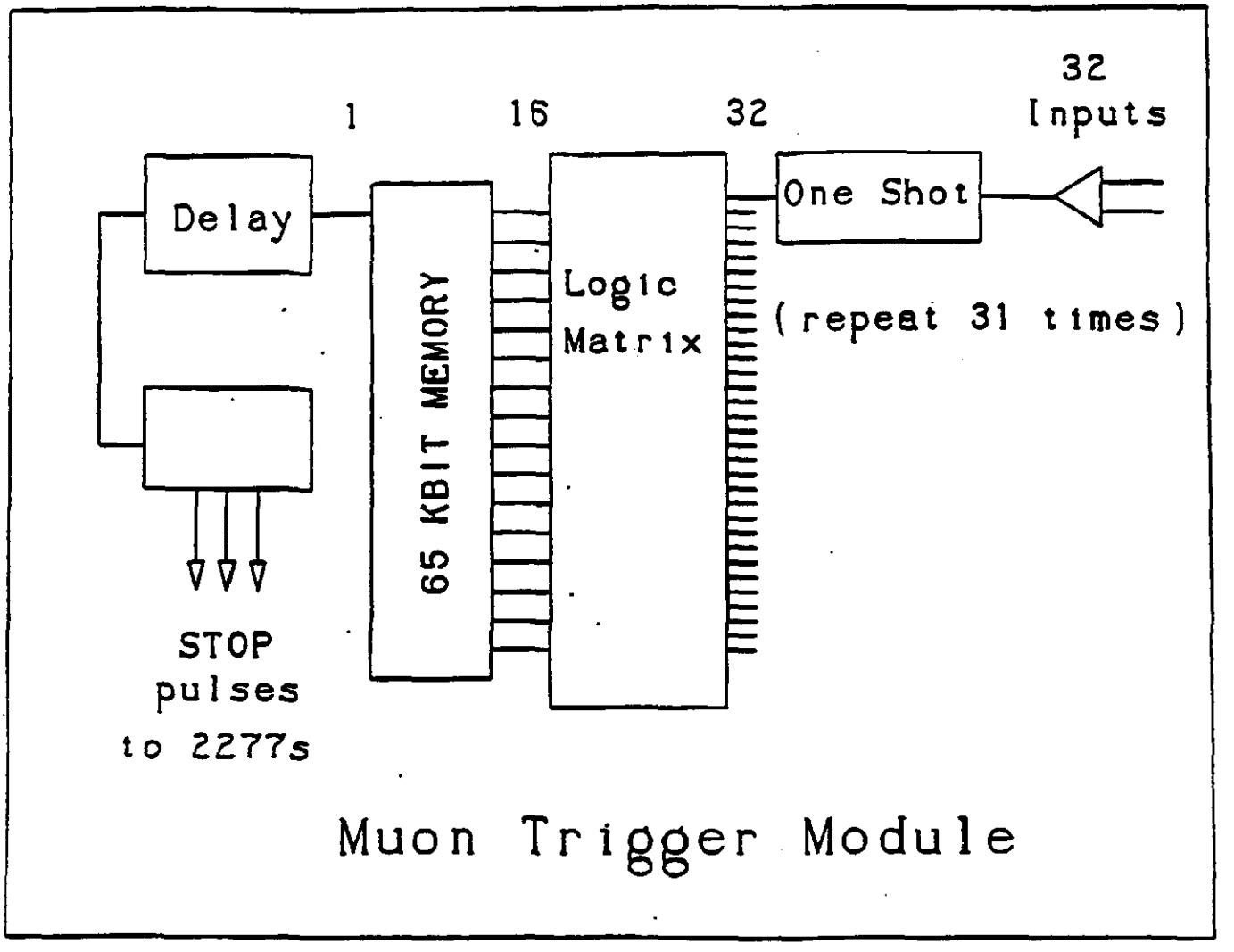
B M BAILEY 4/23/91

D CSC91-04

DRAWING NO.



Elevation of Muon System Volume (Shaded Area)

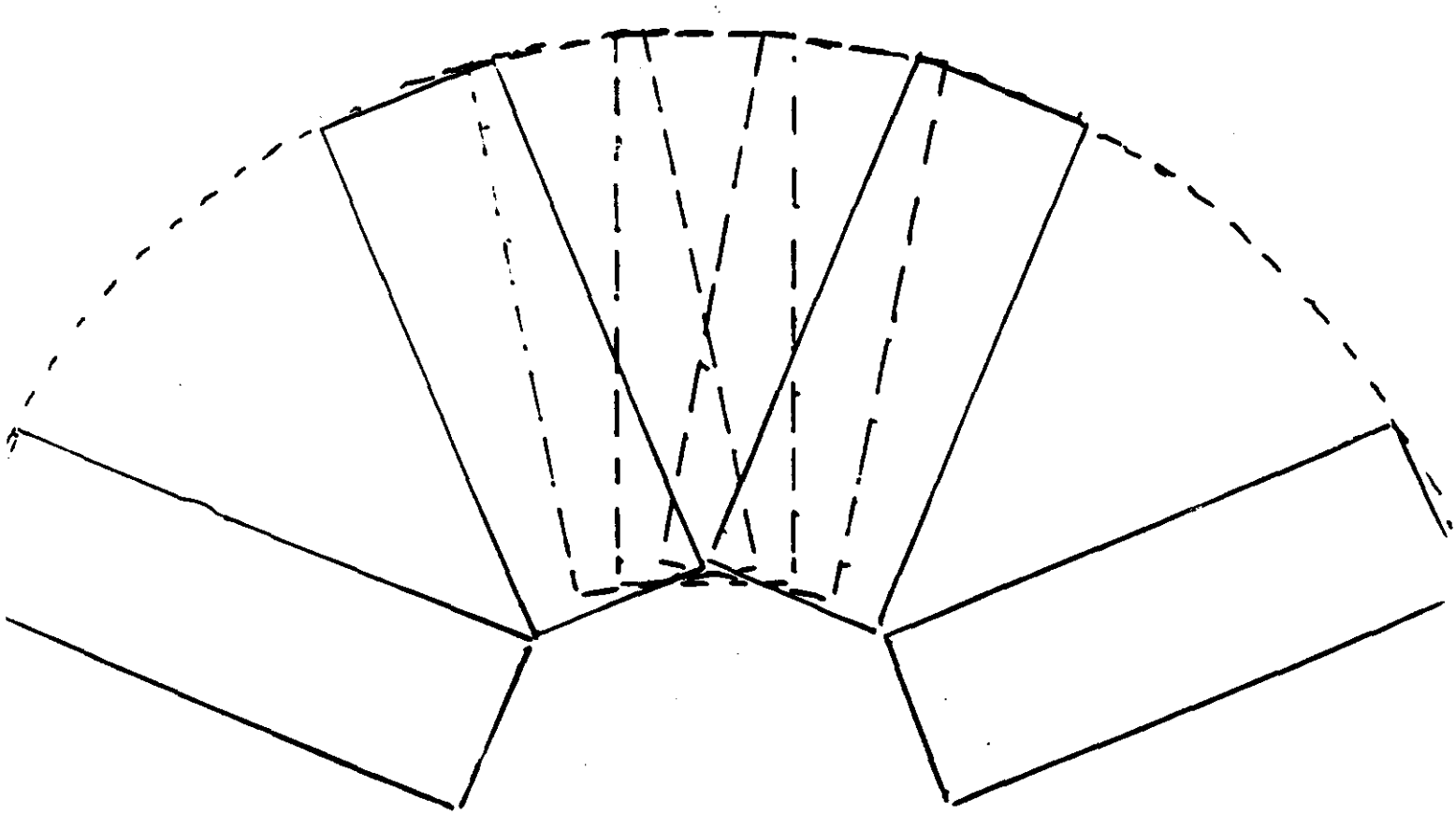


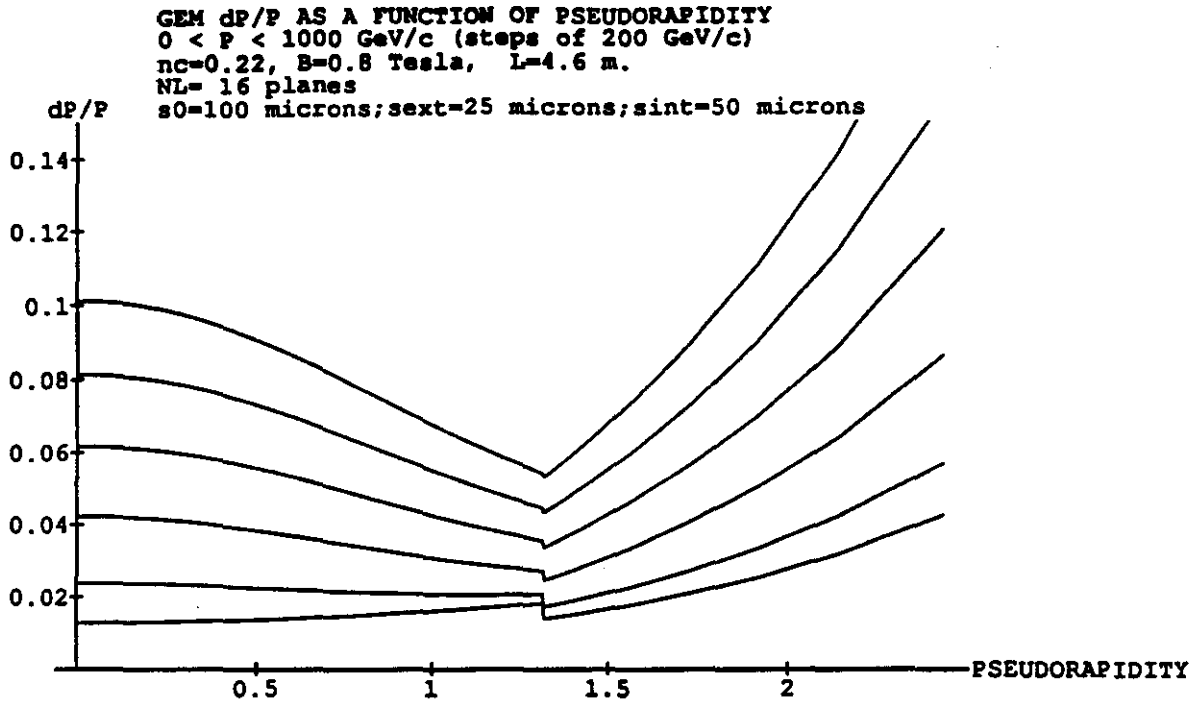
Muon Trigger Module

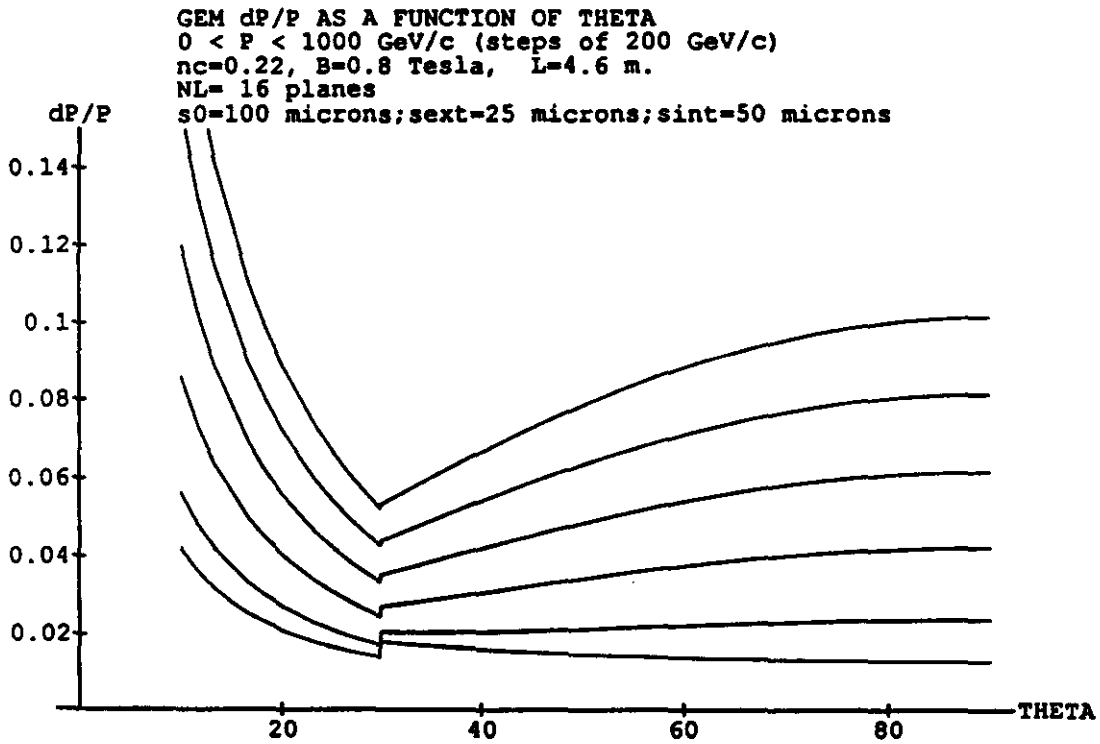
Front & Back Chambers

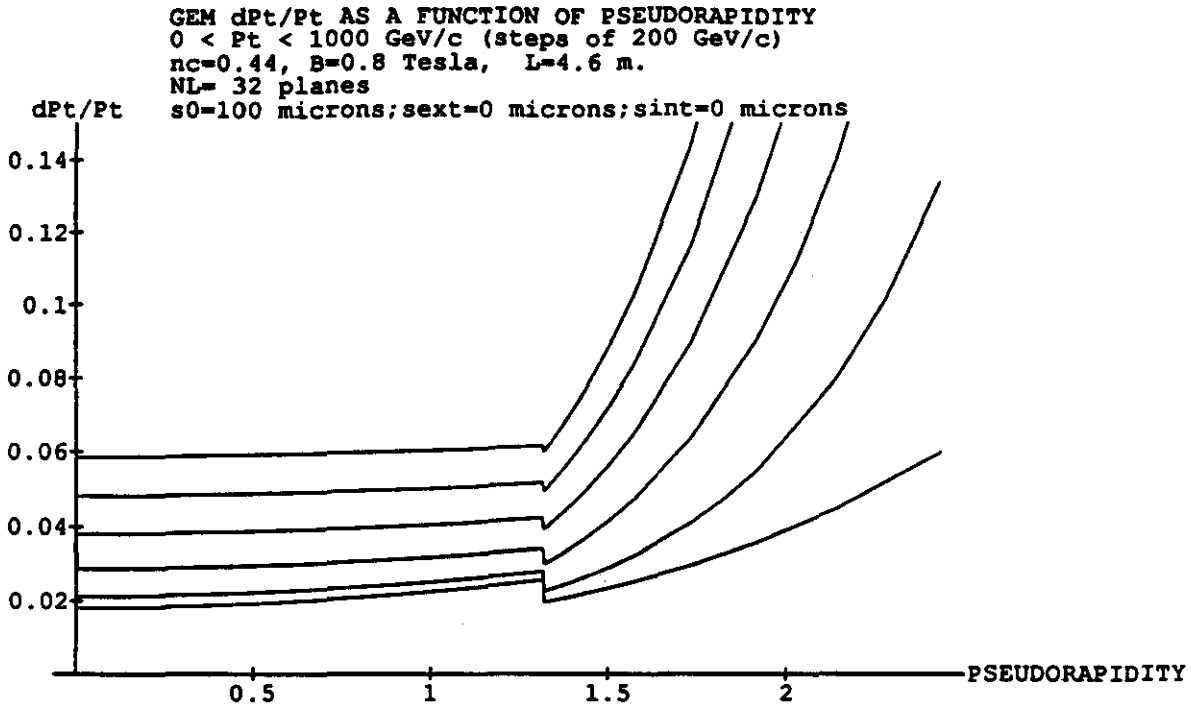
—— Chambers in one plane

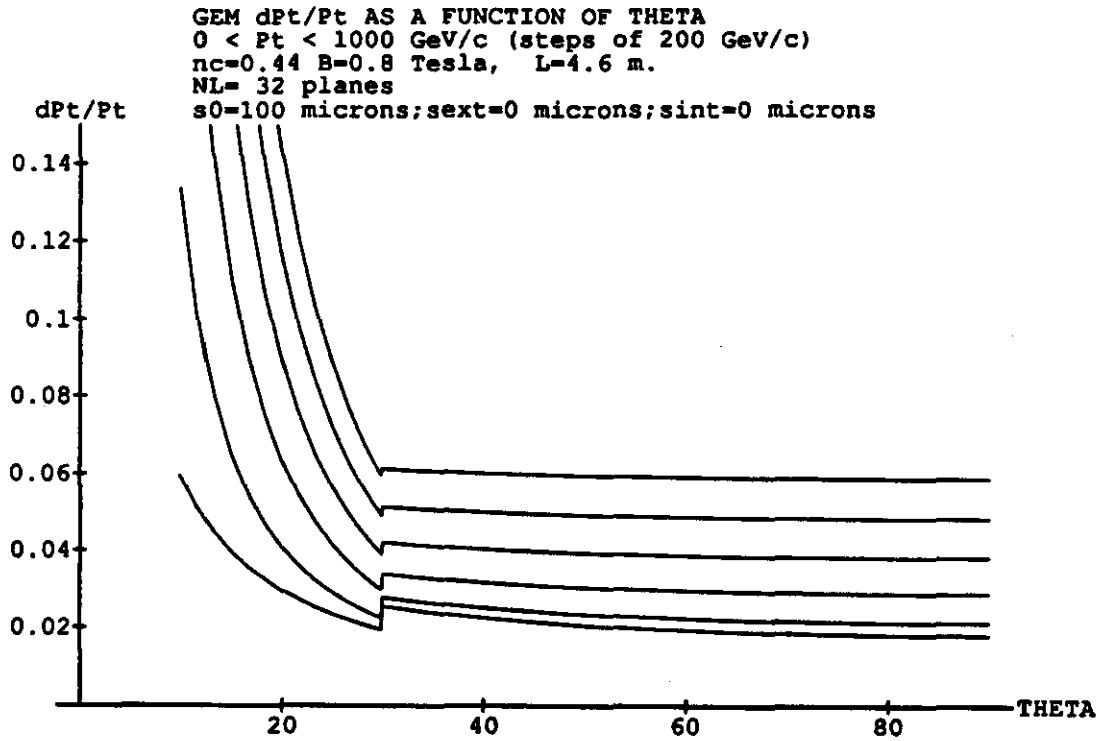
- - - Chambers in other 3 planes




GEM dP/P AS A FUNCTION OF PSEUDORAPIDITY
0 < P < 1000 GeV/c (steps of 200 GeV/c)
nc=0.22, B=0.8 Tesla, L=4.6 m.
NL= 16 planes
s0=100 microns;sext=25 microns;sint=50 microns
dP/P
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0.5
1
1.5
2
PSEUDORAPIDITY


GEM dP/P AS A FUNCTION OF THETA
0 < P < 1000 GeV/c (steps of 200 GeV/c)
nc=0.22, B=0.8 Tesla, L=4.6 m.
NL= 16 planes
s0=100 microns;sext=25 microns;sint=50 microns
dP/P
0.14
0.12
0.1
0.08
0.06
0.04
0.02
20
40
60
80
THETA


GEM dPt/Pt AS A FUNCTION OF PSEUDORAPIDITY
0 < Pt < 1000 GeV/c (steps of 200 GeV/c)
nc=0.44, B=0.8 Tesla, L=4.6 m.
NL= 32 planes
s0=100 microns;sext=0 microns;sint=0 microns
dPt/Pt
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0.5
1
1.5
2
PSEUDORAPIDITY


GEM dPt/Pt AS A FUNCTION OF THETA
0 < Pt < 1000 GeV/c (steps of 200 GeV/c)
nc=0.44 B=0.8 Tesla, L=4.6 m.
NL= 32 planes
s0=100 microns;sext=0 microns;sint=0 microns
dPt/Pt
0.14
0.12
0.1
0.08
0.06
0.04
0.02
20
40
60
80
THETA

Merits of Streamer-Drift System

1. Preservation of the fast rise time in pulse transmission.
2. Open structure for laying down wires-allows multiple wire placement and placement checking for ease of construction.
3. Precision wire positioning.
4. Minimum scattering material.
5. No restriction on chamber length.
6. Parts and assembly amenable to mass production.
7. Stiffness in the final chamber to minimize support points.

8. Single wire resolution of $\sim 100 \mu m$.

Total Costs in m$

Material		
	Chamber bodies	0.14
	Cathodes	0.30
	Bridges	1.00
	z-planes	0.25
Labor		
	Chamber assembly	0.50
	Wiring & testing	2.50
Electronics		12.60
Total		17.29

This is for 4-8-4 wire layer system.

Double the above numbers for 8-16-8

Talk by Erwin Pless

on RPC's

MUON MEETING
B. U.

IRWIN A. PLESS
23 AUGUST 1991

RPCs AND TRIGGER CONSIDERATIONS

INTRODUCTION

1. DESCRIPTION OF RPC STATUS
2. DESCRIPTION OF L* FIRST LEVEL TRIGGER AND MEASURING TECHNIQUE
3. DISCUSSION OF A "WIRE" TRIGGER
   A. ONE WIRE
   B TWO WIRES, TWO PLANES
4. RPC FOR Z- COORDINATE DETERMINATION
5. RPC FOR TRIGGER
6. RPC FOR SAGITTA MEASUREMENT
7. R AND D PROGRAM
8. CONCLUSION

1. DESCRIPTION OF RPC STATUS

A. BAKELITE - R. SANTONICO
B. PVC - C. GUSTAVINO
C GLASS - C. GUSTAVINO

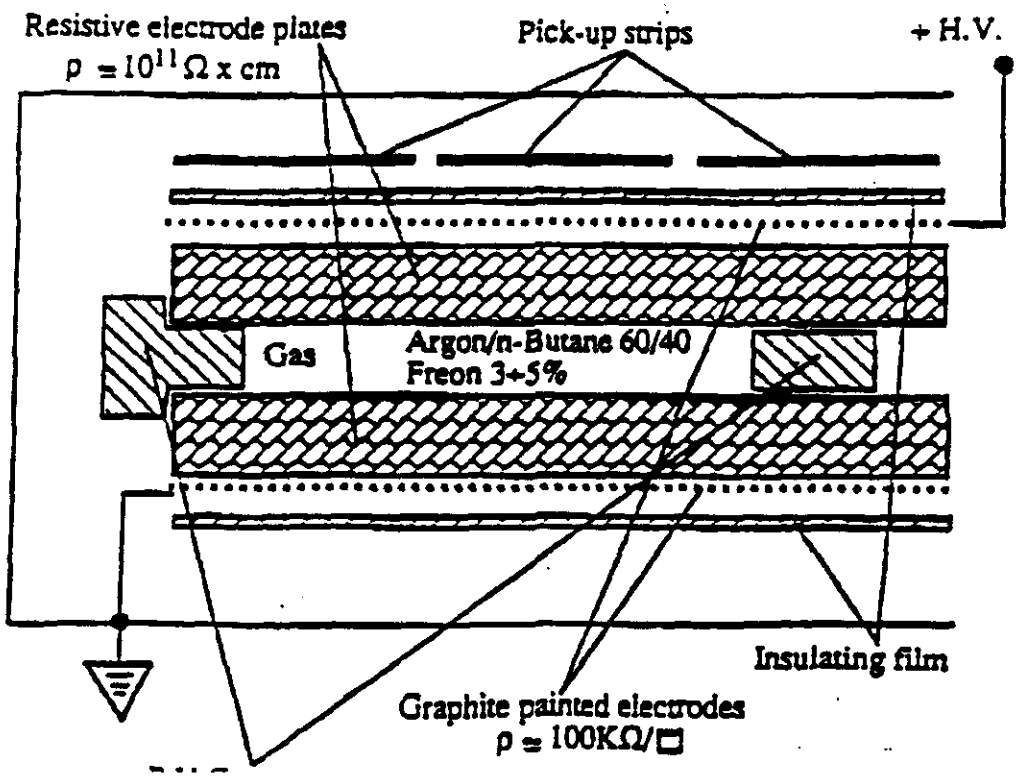
RPC

Table 1 - Characteristics of RPCs	
plate bulk resistivity	$10^{11\pm1}$ Ω cm
electric field	~40 kV/cm
pulse charge	10^2 pC
pulse rise time	~3 ns
pulse duration	~20 ns
efficiency	~97%
discharge area	0.1 cm^2
recovery time	10^{-2} s
time resolution	~1 ns

2. Resistive Plate Chambers

The Resistive Plate Chambers, developped in Rome ten years ago, work at a uniform electric field of ~ 40 kV/cm between parallel electrode plates of a plastic phenolic material (bakelite) with a resistivity $\rho \simeq 10^{11}$ Ω cm. The plates, 2 mm thick, are kept separated at a distance of 2 mm by spacers of polyvinyl chloride. Gas tightness is insured by a frame of the same material. The sensitive volume is filled with a gas mixture of argon/butane plus a small percentage of freon 13B1 at normal pressure. The generating field electrodes are layers of a graphite varnish coating the outer surface of the plates. They are isolated from the read-out electrodes by a 300 μm thick film. A section of the chamber is shown in Fig. 1.

Sketch of a Resistive Plate Chamber



eliminated in the off-line analysis by a cut on the total energy deposited in the calorimeters. 5000 muon events and 15000 pion events of 70 Gev/c momentum were collected.

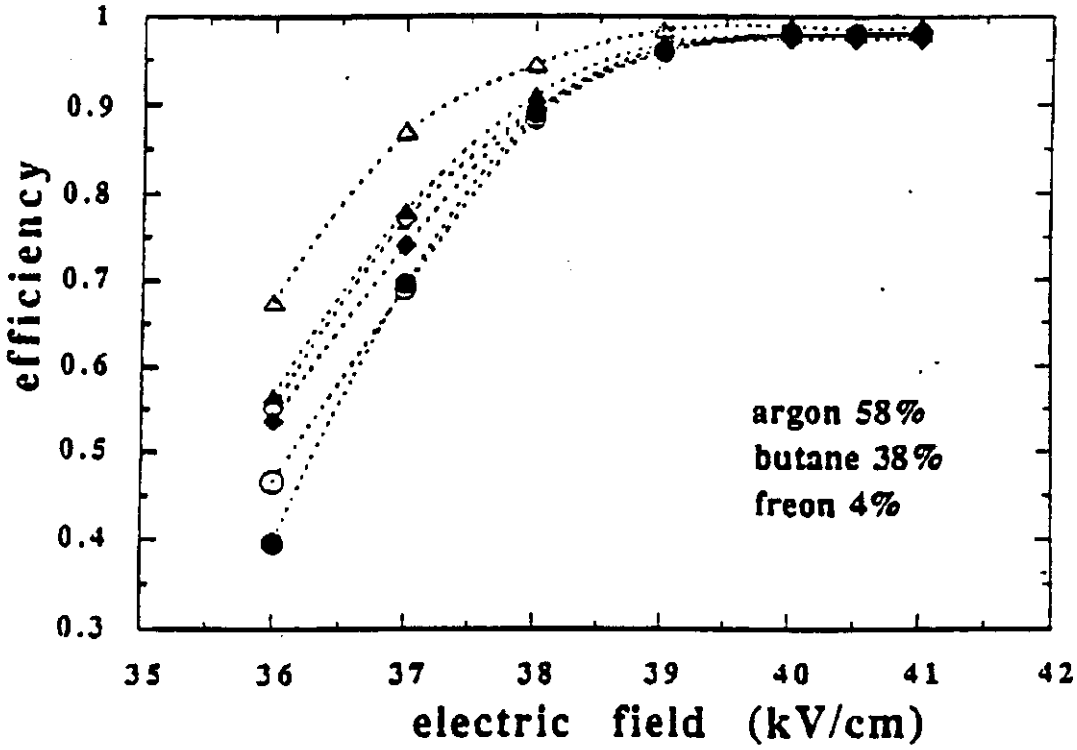


Fig.4 RPCs efficiency versus the applied electric field measured with 70 GeV/c muon events.

5. Chamber efficiency

6 CHAMBERS - 1 X 2 M^2 - 3.1 CM PIT

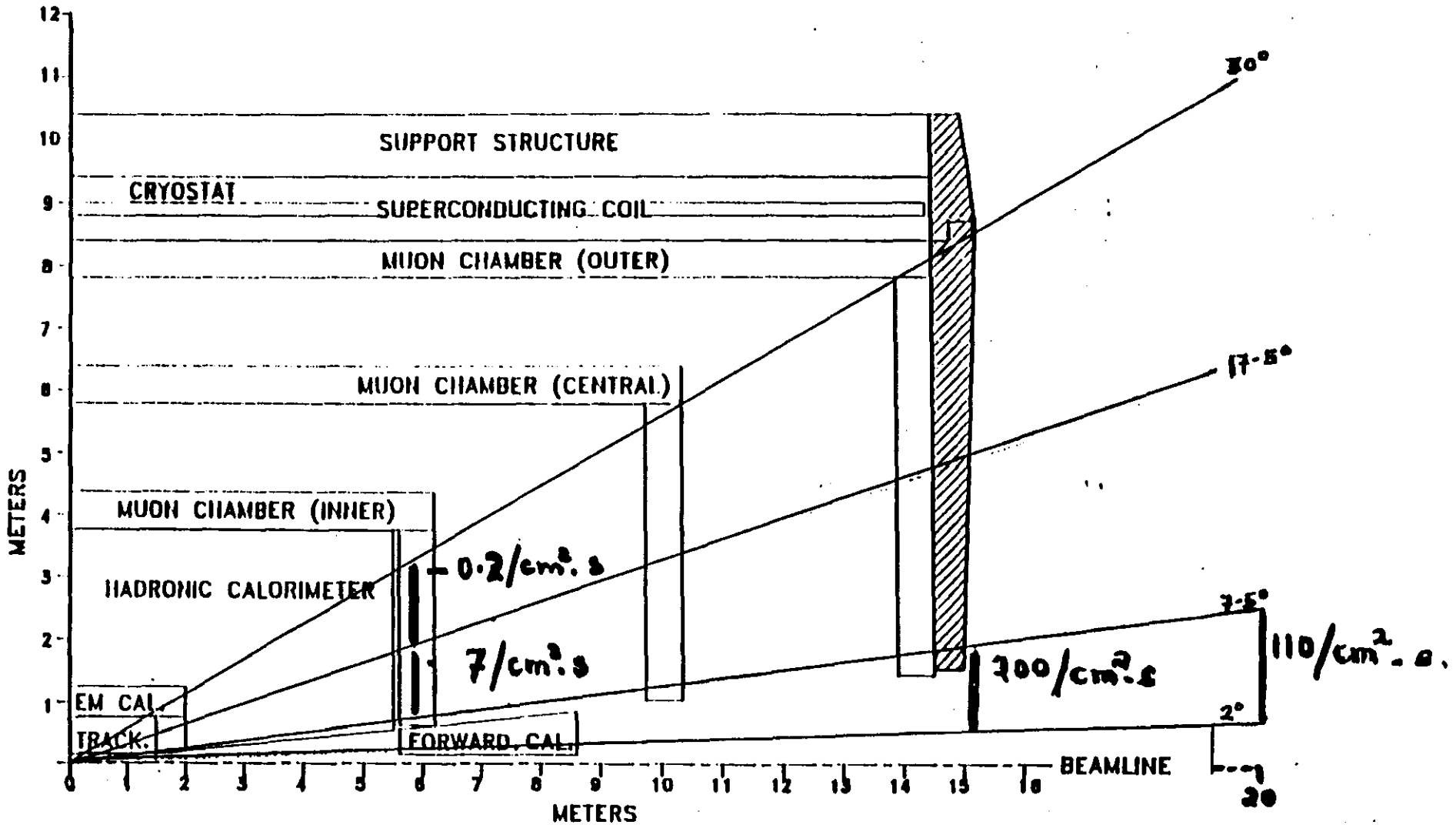
Fig. 4 shows the efficiency of the RPC chambers in the X1 beam as a function of the applied electric field, measured for 70 GeV/c muons. The gas mixture was 58% argon, 38% n-butane and 4% freon. The efficiency for a given chamber was defined as the ratio between the number of times in which a hit was seen in the expected region of the counter and the total number of incident muons. All chambers show an efficiency around 97% for electric fields over 40 KV/cm under a muon flux of about 15 Hz/cm^2. Operation up to fluxes of 40 Hz/cm^2, concentrated over a surface of about 5 cm^2, showed no appreciable degradation of the efficiency.

The out-of-spill rate of the fast-OR was about 10 KHz giving about 0.5% probability of spurious hits per chamber within the 500 ns shaping time. This 'noise' is originated by discharges due to inhomogeneities of the electric field close to the spacers.

6. Tracking with RPCs

Tests have been done to study the tracking capability of RPCs with high energy

L* ESTIMATES
CHARGED PARTICLES
RATE IN MUON CHAMBERS



QUADRANT VIEW OF THE DETECTOR CONCEPT

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH

CERN/DRDC/90-36
DRDC/P7
August 30th, 1990

Study of muon triggers and momentum reconstruction in a strong magnetic field for a muon detector at LHC

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Dept. of HEP, University of Helsinki, Finland

D. Dau
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A. Ferrando, E. Torrente Lujan
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A. Bettini, S. Centro, R. Martinelli, A. Meneguzzo, P. Zotto,
Dipartimento di Fisica, Università di Padova, Italy

C. Bacci, F. Ceradini, G. Ciapetti, F. Lacava, A. Nisati, E. Petrolo, L. Pontecorvo, S. Veneziano and L. Zanello
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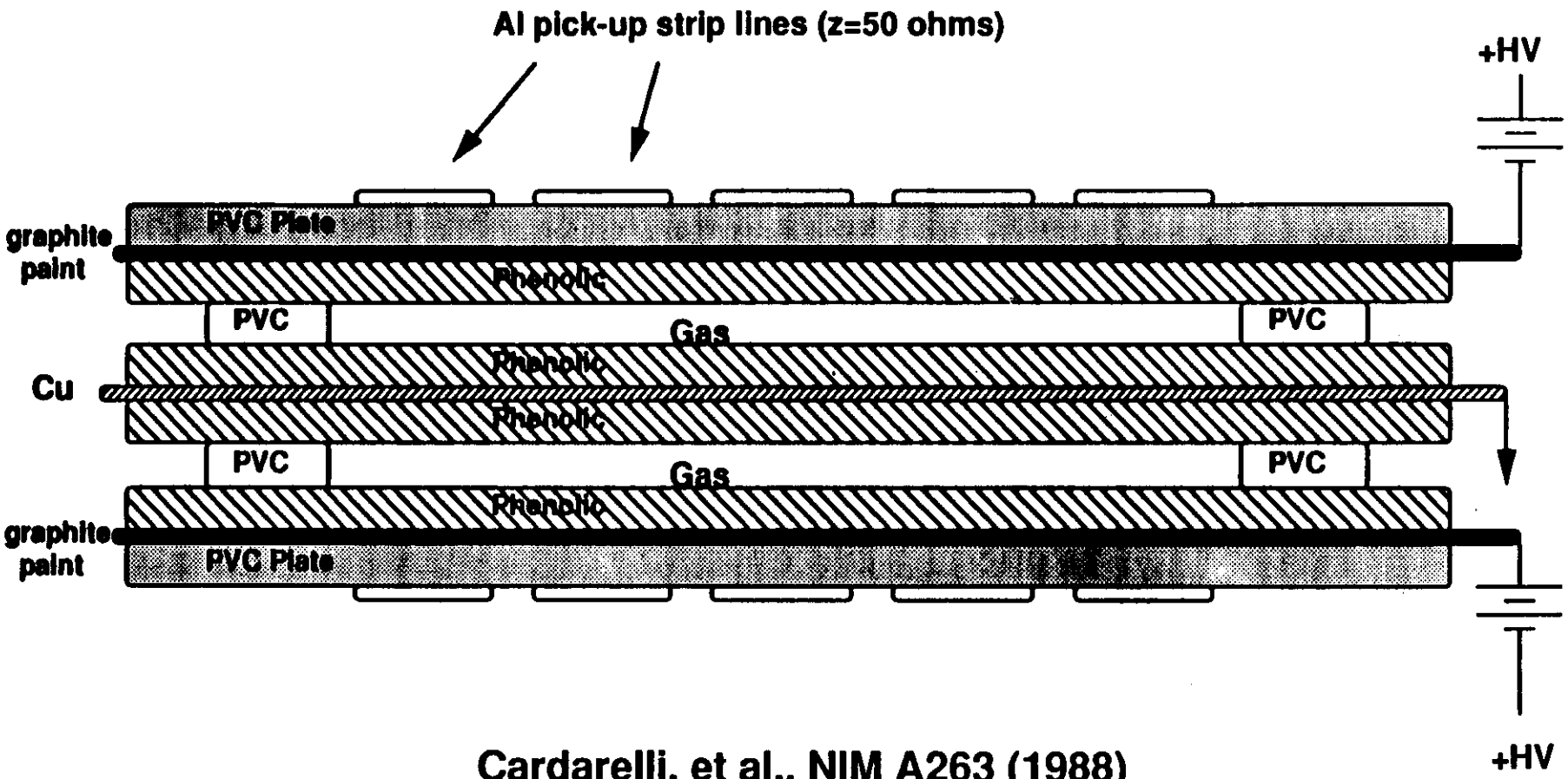
F. Szoncso, G. Walzel, C.- E. Wulz
HEPHY, Österreichische Akademie der Wissenschaften, Vienna, Austria

R&D proposal
subject to approval by the Funding Agencies

[1] Joint spokesmen



Cardarelli, et al., NIM A263 (1988)

ISTITUTO NAZIONALE DI FISICA NUCLEARE

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Assergi,
S.S. 17/bis Km 18+910 67010 ASSERGI (AQ) Italia
Tel. 0862/4371 - Telefax 0862/606613 - Telex 600330

MEMORANDUM (91.08.07)

To: F. Ceradini
R. Santonico

From: I.A. Pless

Subject: Discussions on the Research and Developement of Resistive Plate Counters

Date: 7 August 1991

The purpose of this memorandum is to recall our conversations of the 30 and 31 of July 1991 at CERN.

We talked about the various aspects associated with the construction and operation of RPCs. The research and developement program, RD5, was discussed. The interest of the SSC GEM detector collaboration was explained. A possible joint, and complementary, research and developement program was formulated. The basic agreement was along the following lines:

1. MIT, working within the GEM collaboration, would set up an RPC test station.
2. The GEM collaboration would measure the spacial resolution of an RPC as a function of the length of the readout strips. In particular, the effect of a six meter (or longer) readout strip would be measured. To start, a simple cosmic ray telescope would be used and a comparison of the charge distribution created by a cosmic ray muon would be made at the two ends of the read out strip. At some future date the equipment could be tested at the MIT Bates linear accellerator.
3. F. Ceradini and R. Santonico will assist Irwin A. Pless in acquiring all the components needed to set up a "standard" one meter by two meter RPC. This "standard" RPC will be assembled at MIT and the performance will be compared to the expected performance before making further tests. F. Ceradini and R. Santonico will also assist Irwin A. Pless in acquiring two dummy RPCs so as to make the resolution measurements realistic.

4. The GEM collaboration will be responsible for all electronic components and other expenses required to make all relevent measurements.
5. All data and experiences learned in this test program will be freely available to all members of this joint collaboration.

I trust this represents the spirit of our discussions. Any corrections or additions to this memo will be warmly received.

Sincerely yours,

Irwin A. Pless

Irwin A. Pless
Professor of Physics
MIT

Nuclear Instruments and Methods in Physics Research A270 (1988) 190–193
North-Holland, Amsterdam

PLASTIC SPARK COUNTERS WITH PVC ELECTRODES

G. BATTISTONI, P. CAMPANA, U. DENNI, C. GUSTAVINO and E. IAROCCI

Laboratori Nazionali di Frascati dell' INFN, Frascati, Italy

Received 16 September 1987 and in revised form 4 January 1988

The performance of a spark counter based on plasticized PVC is described. The relevant features of this detector match the requirements of surface and underground cosmic ray experiments. Its technological characteristics allow large area detector construction.

1. Introduction

In the framework of the study of new apparatus for extensive air showers of cosmic rays, we have considered the application of spark counters. For this purpose a time accuracy of the order of only a few nanoseconds is required [1]. Low cost, reliability and easy monitoring are of relevant importance.

So far the development of plate spark counters [2] with resistive electrodes has shown the possibility of reaching high time accuracies and good space resolution at the same time, but their use has been limited by the strict technological requirements due to the high gas pressure and to the degree of mechanical tolerances needed for gaps of 0.1–0.2 mm. They require electrode materials with volume resistivity in the range 10^9–10^{11} Ω cm, with a sufficient degree of homogeneity; for this purpose some resistive glasses have been successfully proposed, but they are rather expensive and not easily available. In practice all these limitations become prohibitive for large area counters.

In order to reduce the technological difficulties a new type of resistive plate counter (RPC) [3] has been developed, to be employed whenever a time resolution of the order of hundreds of picoseconds is sufficient. In this detector the resistive electrodes are made out of a phenolic thermosetting resin denominated Bakelite. The counter gap is of the order of 1.5–2 mm, and the gas circulation is at atmospheric pressure. Anyway, the RPCs, as the other spark counters, exhibit a noisy operation, i.e. the production of spurious sparks, and the use of thermosetting materials is restrictive as far as the construction technology is concerned.

We describe here a new plastic spark counter based on plasticized PVC. While rigid (unplasticized) PVC has a volume resistivity of the order of 10^{15} Ω cm, the addition of plasticizers to obtain the standard commercial soft PVC, lowers resistivity down to 10^{11}–10^{12} Ω cm [4]; by doping with ionic compounds, a volume resistivity around 10^{8} cm can be easily achieved [5]. We show that the use of commercial plasticized PVC allows the construction of spark counters with noiseless operation and time resolution of the order of 1 ns. Furthermore the use of a material such as PVC makes it possible to exploit the thermoplastic material technology which allows easy construction procedures for large area counters.

2. Prototype description

Fig. 1 shows the cross section of one prototype. The active volume containing the gas mixture is delimited by two parallel plate electrodes made of plasticized PVC, 1 mm thick. The volume resistivity is $\sim 10^{11}$ Ω cm. High voltage is supplied to the PVC electrodes by means of a graphite coating on the surface not in contact with the gas. The varnish is a commercial solution of graphite in methyl-isobutyl-ketone, and the surface resistivity is ~ 10 k$\Omega/\square$. A copper strip provides the electrical contact with the high voltage. The graphite-coated surface

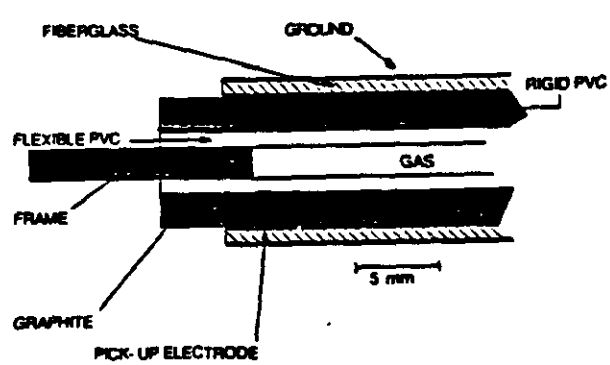

Fig. 1. Cross section of a spark counter prototype.

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(North-Holland Physics Publishing Division)

7

1991

Nuclear Instruments and Methods in Physics Research A300 (1991) 572–57
North-Holland

Glass electrode spark counters

M. Anelli, G. Bencivenni, G. Felici and L. Magro
*Laboratori Nazionali di Frascati * – INFN, Frascati, Italy*

Received 6 August 1990

We have developed and investigated the behaviour of a spark counter based on low cost resistive glass electrodes.

1. Introduction

The need of large area detectors with a time accuracy of the order of only a few nanoseconds is foreseen in apparatus for extensive air showers. They could also be used as external muon detectors in a high rate environment, like future collider experiments. In both cases the proposed detector must have uncritical conditions concerning high voltage, a high reliability and low cost of both the detector and front-end electronics.

Planar spark counters with very good time resolution (≤ 50 ps) using semiconductive glass ($\rho \sim 10^{7}$–10^{10} Ω cm) as electrodes have been developed in Novosibirsk [1]. They are mainly used for particle identification at energies around 1 GeV, but their relatively high cost and construction difficulty, due to the strict technological requirements (i.e. mechanical problems correlated with gaps of 100–200 μm and high gas pressure operation), make them unfeasible for very large area detectors.

A more simple to construct planar counter (gaps of 1.5–2 mm and gas mixtures at atmospheric pressure) with a lesser time resolution, has been developed [2] using bakelite ($\rho \approx 10^{11}$ Ω cm) as resistive electrodes. However, a serious problem of this kind of detectors is its noisy operation, probably due to the material used. To overcome these problems we have developed a new type of detector with a gap of about 2 mm operated at atmospheric pressure and based on low cost resistive glass electrodes.

2. Spark counter prototype description

Two spark counter prototypes have been built; their cross section is shown in fig. 1. The parallel electrodes

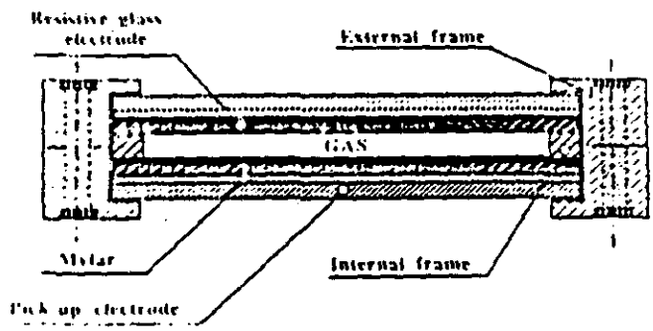

Fig. 1. Cross section of the glass electrode spark counter prototype.

are made of resistive glass with a volume resistivity of 6×10^{11} Ω cm, and a thickness of 2 mm. The external side of the glass is varnished by a solution of graphite in water, in order to supply a high voltage. A glass–epoxy frame, 1.6 mm thick and 10 mm wide delimits the active surface of 10×10 cm^2. Due to the small dimensions and the good mechanical characteristics of the material used the chambers do not need extra spacers. The electrode transparency effect [3] allows the induced pulses to be read by pickup electrodes (surface of 10×10 cm^2) placed on both sides of the chambers.

3. Experimental results

Fig. 2 shows the singles counting rate plateau as a function of high voltage, obtained with one of the two prototypes after a very short time of burning in (some hours). The gas mixture used during these measurements is an Ar (60%) + C_4H_{10} (38%) + Freon 13B1 (2%). The discriminator threshold applied on the signal is 20 mV/50 Ω and the electronic dead time is 5 μs. A plateau width of about 700–800 V is obtained, showing the possibility of a wide noiseless operating range. It must be stretched in accordance with the main require-

* This work has been done in the framework of FESTE group activities.

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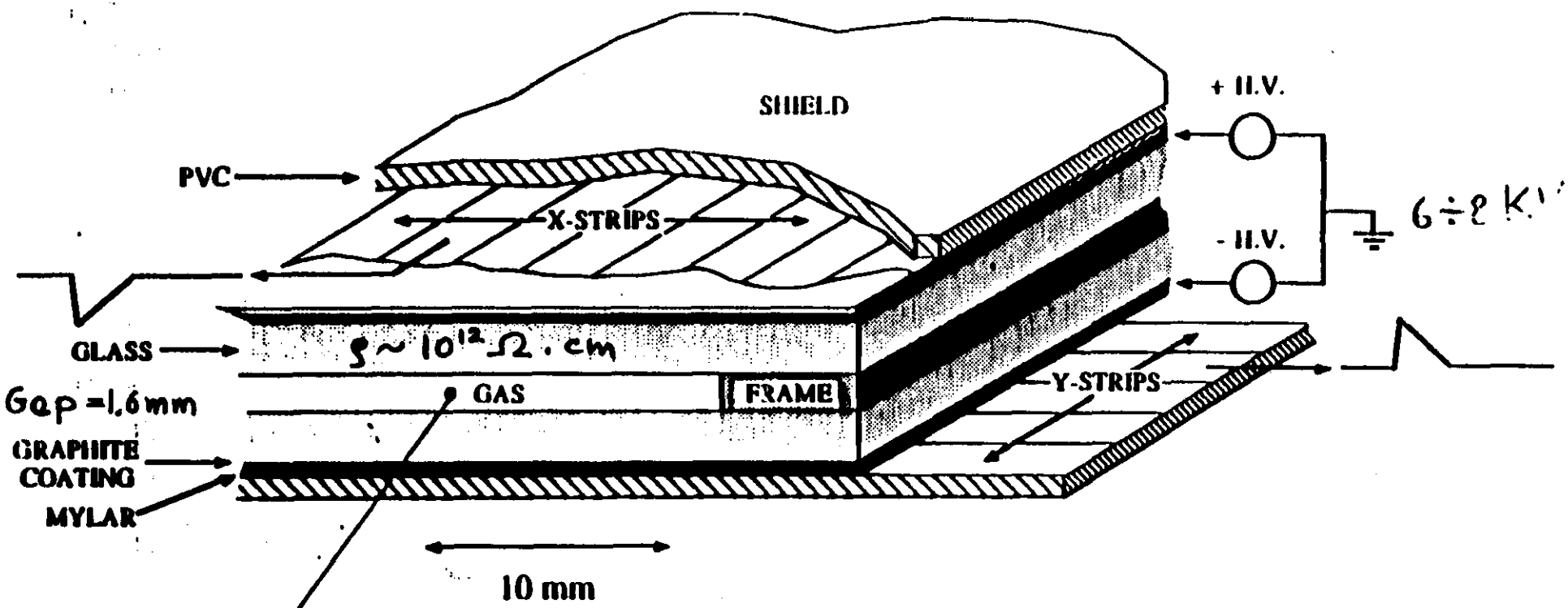
GLASS ELECTRODE SPARK COUNTERS AND THEIR USE IN LOW ENERGY CALORIMETER (DAΦNE)

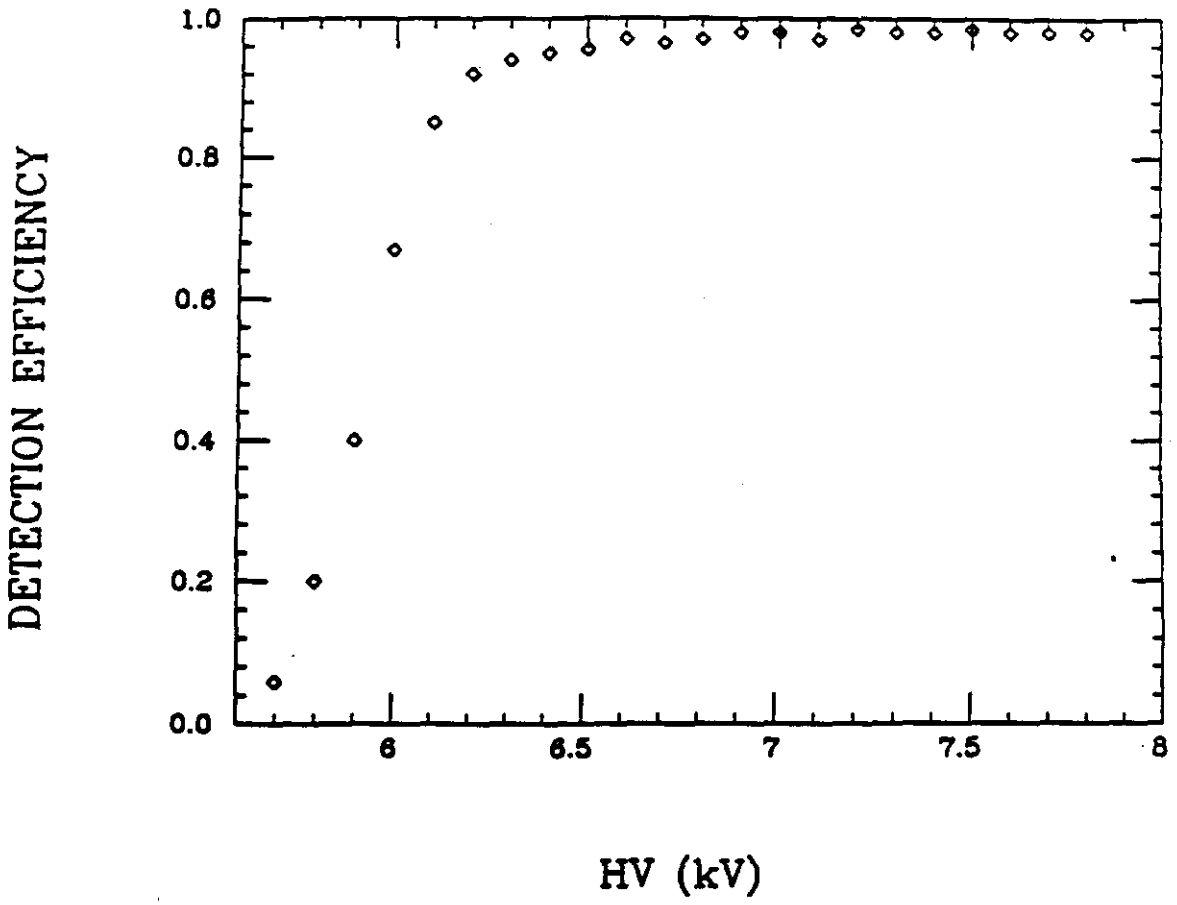
G. Bencivenni
M. Benfatto
V. Chiarella
G. Felici
C. Gustavino
A. Martini
E. Pace
A. Stecchi
L. Trasatti

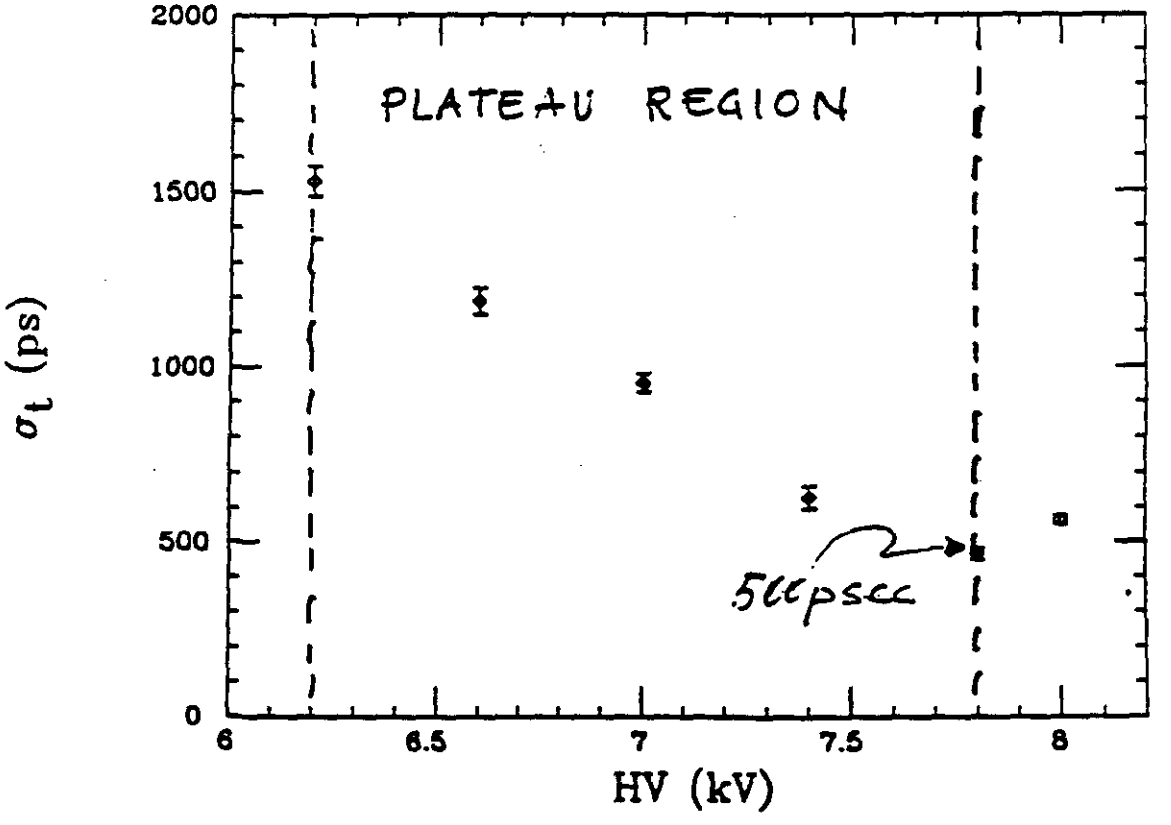
Glass Spark Counter *



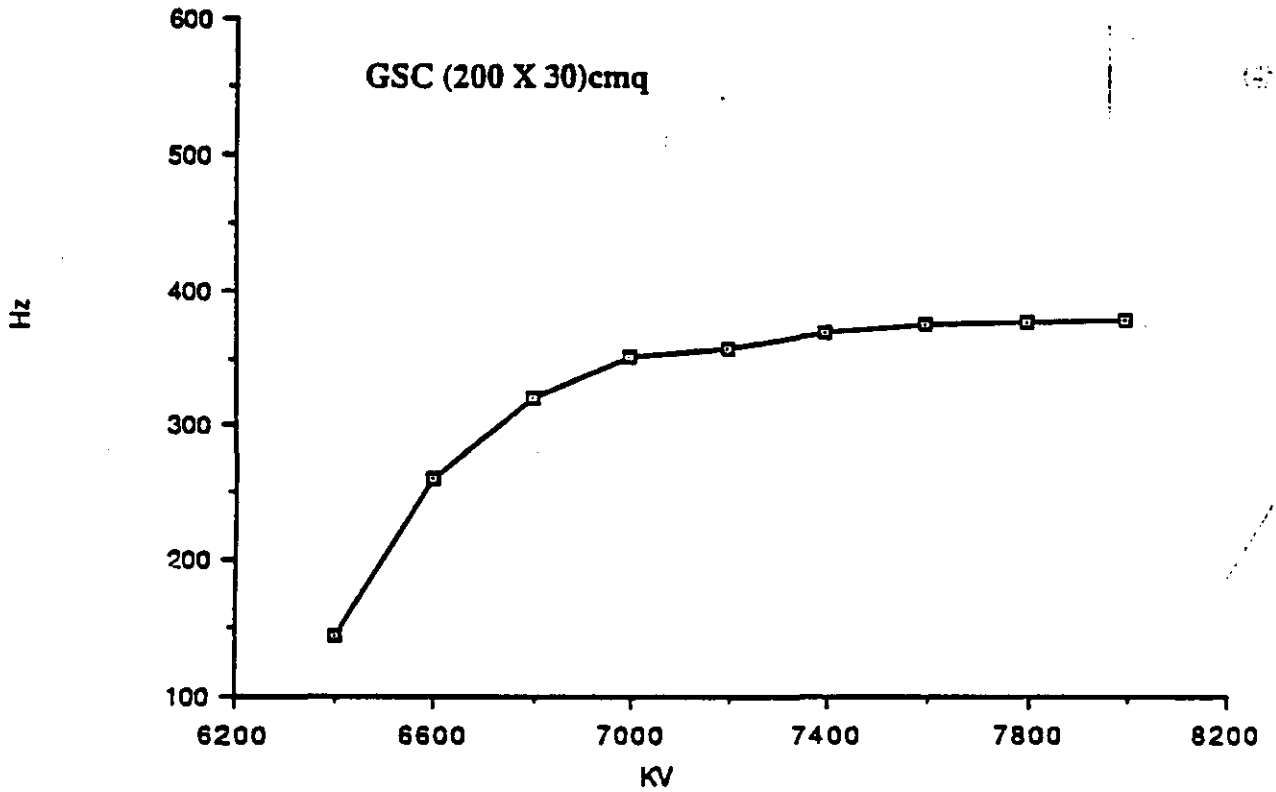
Ar/Iso/Freon = 60/38/2

* R&D project for a new version of large gap parallel plate counters (GLASS)


DETECTION EFFICIENCY
1.0
0.8
0.6
0.4
0.2
0.0
6
6.5
7
7.5
8
HV (kV)


PLATEAU REGION
500psec
2000
1500
1000
500
0
6
6.5
7
7.5
8
HV (kV)
σ_t (ps)

VERY PRELIMINARY
NO TRIGGER COUNTING RATE



Ar = 60 %

Iso = 38 %

Freon = 2 %

thr = 10 mV

e.D.T = 1 μS

2. DESCRIPTION OF L* FIRST LEVEL TRIGGER AND MEASURING TECHNIQUES

A. EOI p. 35 - TRIGGER

B. CENTRAL MEASUREMENT

PRECISE - AXIAL WIRES

COURSE - TRANSVERSE WIRES

TRIGGER - 3 CM AXIAL STRIPS

C. END CAP MEASUREMENT

PRECISE - X WIRES

PRECISE - Y WIRES

TRIGGER - 3 CM RADIAL STRIPS

D. FORWARD

PRECISE - VERTICAL WIRES

COURSE - HORIZONTAL WIRES

TRIGGER - 2 CM VERTICAL STRIPS

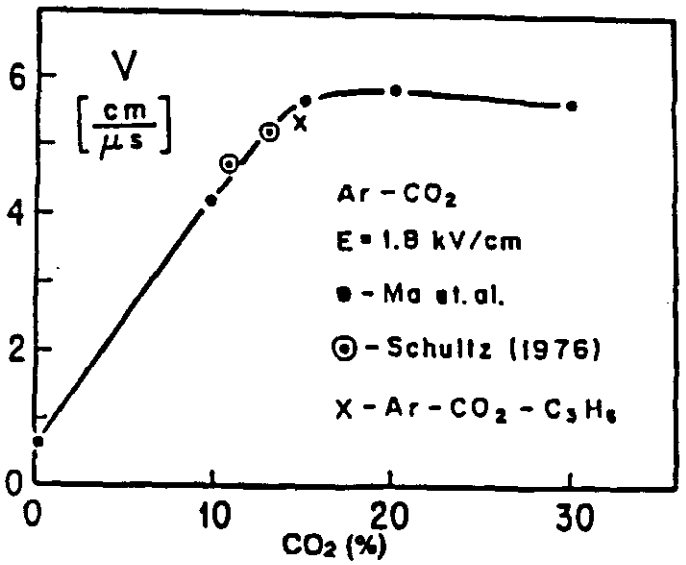


Fig. IV.22. Drift velocity (v) vs CO_2 concentration. The electric field E is 1.8 kV/cm.

resolution requirements and could be used in the central detector. This already operational system of 25k channels cost 190$ per channel, including all cabling, interfacing, readout, and monitors. However, the increase in channel number from L3 to L* is of an order of magnitude. This creates a need for R&D to achieve high component density, cabling reduction, reliability, easy diagnostics and repair, and low cost.

In addition, the complexity of the L* muon spectrometer requires the development of a large number of electronics systems monitoring all the relevant parameters. In particular, the high-voltage system has to be distributed and controlled to react to background conditions in order to avoid wire damage and aging.

C.6. Muon Trigger Generation

The fast level 1 muon trigger will be derived from three coincident layers of Resistive Plate Counters (RPCs) (Ref. IV.18). These devices produce a very fast (10 ns) discharge in a gaseous gap of 2 mm after passage of an ionizing particle. Induced signals are received on external strips and yield a precise timing resolution of 2–3 ns. RPCs and their associated electronics provide a low cost method of instrumenting the very large area required (i.e., 4000 m^2). Three RPC layers will be attached to the muon chambers in the central region. They will be read out by 3-cm strips oriented parallel to the magnetic field. RPC layers with 3-cm radial pick-up strips are also connected to the muon chambers in the endcap regions, and RPCs with 2-cm strips running vertically (parallel to the magnetic field) are placed at three positions in the forward detectors. Fast (i.e., 100 ns) logic searches for tracks pointing to the interaction region along fiducial "roads" in the r-ϕ plane, which specify a particular momentum cut. The precise time resolution of RPCs also enables cosmic ray triggering and flagging.

After the 1-μs maximum drift time has elapsed (i.e., during the level 2 trigger), candidate tracks are also formed using muon chamber hits. A track finder will identify muons within roads that span both bending and nonbending coordinates. These roads point back at the interaction region and are determined by coincident hits (mutually arriving within 1 μs) on selected wires in the outer and inner layers of drift chambers. Roads are assembled for each module in the central region by demanding hits in z-layer wires within narrow (2°) intervals in θ, as implemented at L3. Roads are defined in a similar fashion to detect tracks in the endcap regions, where limits in θ and ϕ will be imposed by requiring hits in orthogonal chamber wires lying within the solid angle defined by each road. In the forward detectors, roads are again subdivided in θ and ϕ by requiring hits in orthogonal chamber wires. Road boundaries will be set more narrow in this region, in order to clearly separate individual tracks and avoid accepting lower momentum particles.

Muon chamber data can be assigned to particular events by linking candidate tracks found in the muon chambers within the 1-μs drift interval to those found in the RPC array and/or hadron calorimeter. In addition, matching of candidate tracks with particular events can be rapidly accomplished by performing time sum calculations for hits in adjacent chamber layers that are offset by half of a cell width (Fig. IV.18). The sum of drift times resulting from the offset chamber layers, plus a correction term proportional to the tangent of the angle between the track and chamber plane (known from the road definition), should always be equal to the maximum drift time, that is, 1 μs. Rapid computation of a time sum for each candidate track will enable every track to be correlated with a particular event, or a range of events in the cases where uncertainties (i.e., in the incident angles) are large.

C.7. Alignment Systems

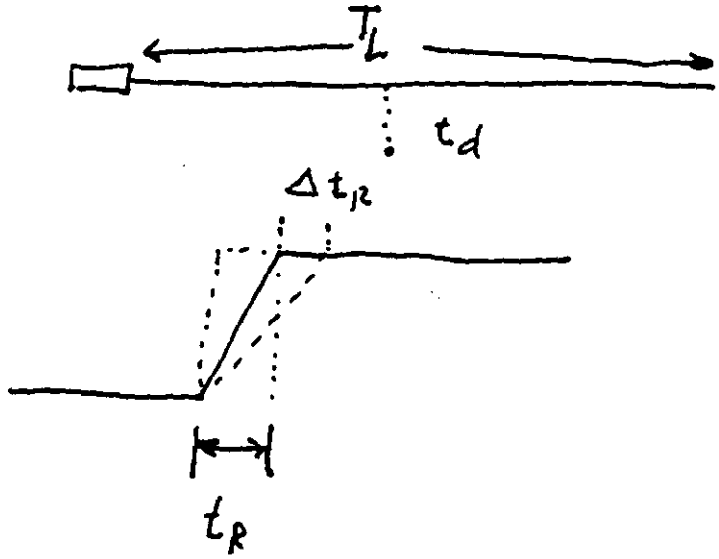
Throughout the evolution of L3, numerous techniques, instrumentation and test fixtures were employed or developed to obtain the required alignment accuracies. The L3 experience provides a significant knowledge base by which to judge the strengths and drawbacks of proposed alignment techniques or systems and to make specific recommendations of R&D efforts needed for improvements which might otherwise be overlooked or discovered late in the detector's development.

Local Alignment System

The function of the local system is to align chambers within a module. In each of the three muon detector regions (central, endcap, and forward), chambers are grouped into sets of three equidistant layers for the purpose of muon sagitta measurement. The middle layer actually consists of two chambers that are joined one on top of the other and referenced during fabrication such that they may be considered as one chamber for alignment purposes. Each of the three chamber layers measures the particle track precisely in the bending direc-

3. DISCUSSION OF A "WIRE" TRIGGER

A. ONE WIRE



$$\text{RESOLUTION} = \sqrt{(\Delta t_R)^2 + (T_L)^2}$$

PROPAGATION TIME $\cong$ 3.3-5 NANOSECONDS / METER

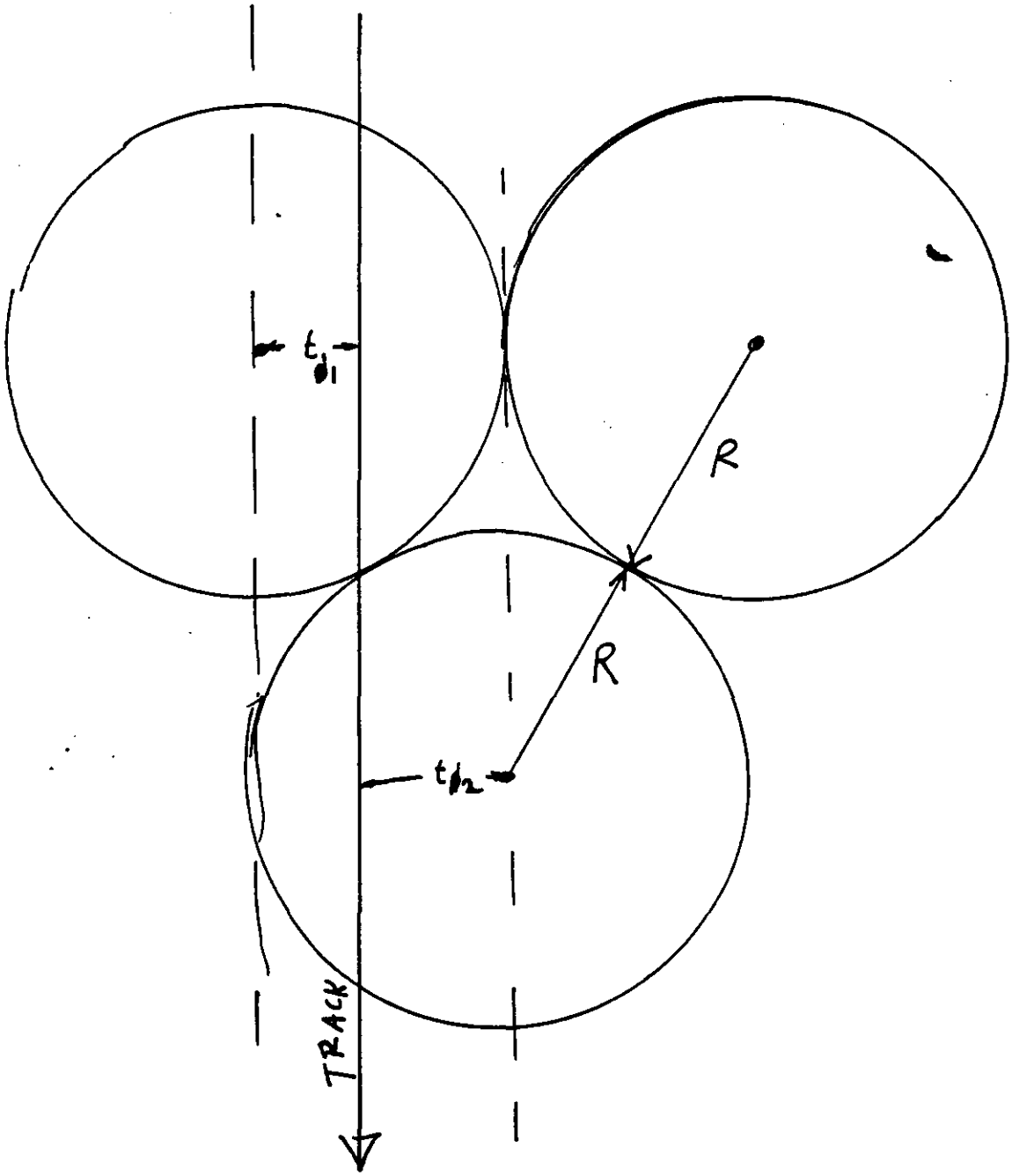
$L \cong$ 6 METERS

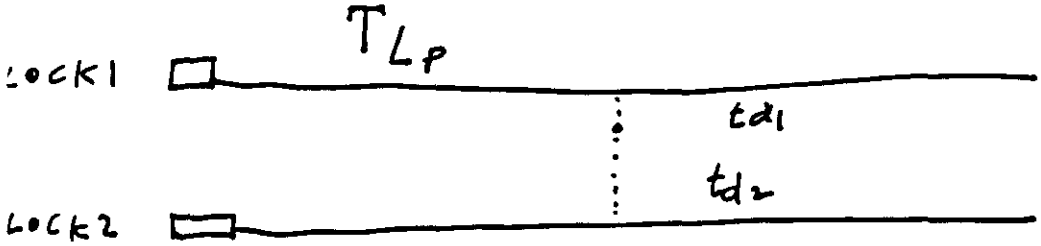
$T_L \cong$ 20-30 NANOSECONDS

$\Delta t_R \cong$ 2-4 NANOSECONDS

HENCE LENGTH OF WIRE LIMITS THE RESOLUTION

B. TWO WIRES, TWO PLANES





$T_{LP} + t_{d_1} \Rightarrow$ CLOCK 2 STARTS

$T_{LP} + t_{d_2} \Rightarrow$ CLOCK 2 STOPS

CLOCK TWO $= \Delta T_d = T_{LP} + t_{d2} - (T_{LP} + t_{d1}) = t_{d2} - t_{d1}$

$$\Delta T_d = t_{d2} - t_{d1}$$

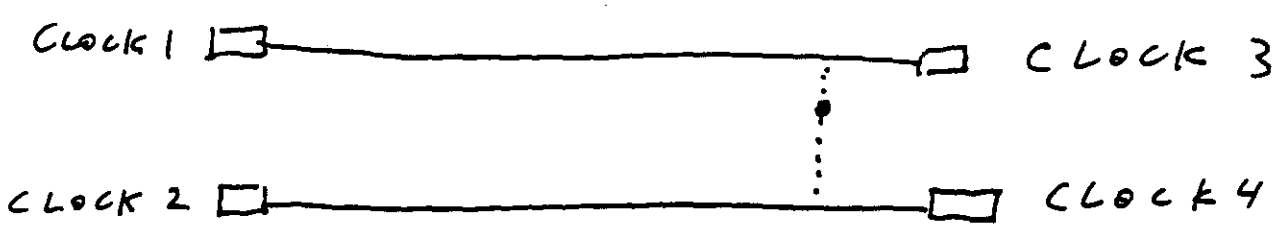
TOTAL DRIFT TIME $= T_D$

$$T_D = t_{d2} + t_{d1}$$

$$\Delta T_d + T_D = 2t_{d2}$$

$$t_{d2} = \frac{\Delta T_d + T_D}{2}$$ (MEAN TIME)

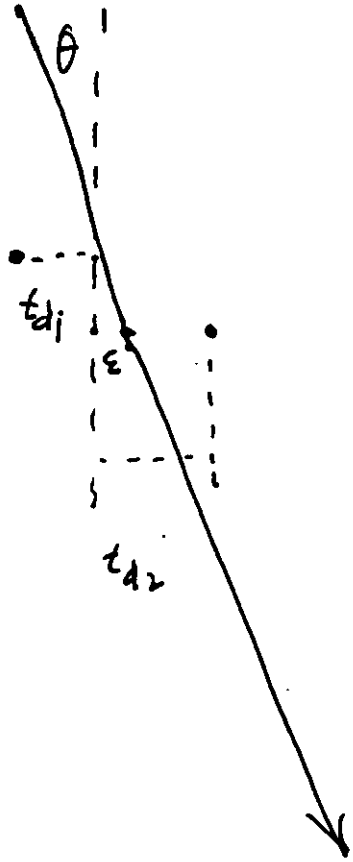
NEED T_{LP} TO COMPLETE TRIGGER



$$T_{LP} = \frac{\Delta T_L + T_L}{2}$$

WITH A CLOCK AT THE END OF EACH WIRE ONE CAN GET A TRIGGER IN 16 NS

BUT WHAT HAPPENS IF THE TRACK COMES IN AT AN ANGLE $\theta \neq 0$



$T_{LP} + t_{d_1} \Rightarrow$ CLOCK 2 STARTS

$T_{LP} + (t_{d2} - \varepsilon) \Rightarrow$ CLOCK 2 STOPS

$$\Delta T_d = t_{d_2} - \varepsilon - t_{d_1}$$

$$\Delta T_d = t_{d_2} - t_{d_1} - \varepsilon$$

$$T_D = t_{d_2} + t_{d_1}$$

$$t_{d_2} = \frac{\Delta T_d + T_D - \varepsilon}{2}$$

$$t_{d_2} = \frac{\Delta T_d + T_D}{2} - \frac{\varepsilon}{2}$$

$$\varepsilon = \frac{(2R \cos 30^\circ) \tan \theta}{\text{DRIFT VELOCITY}}$$

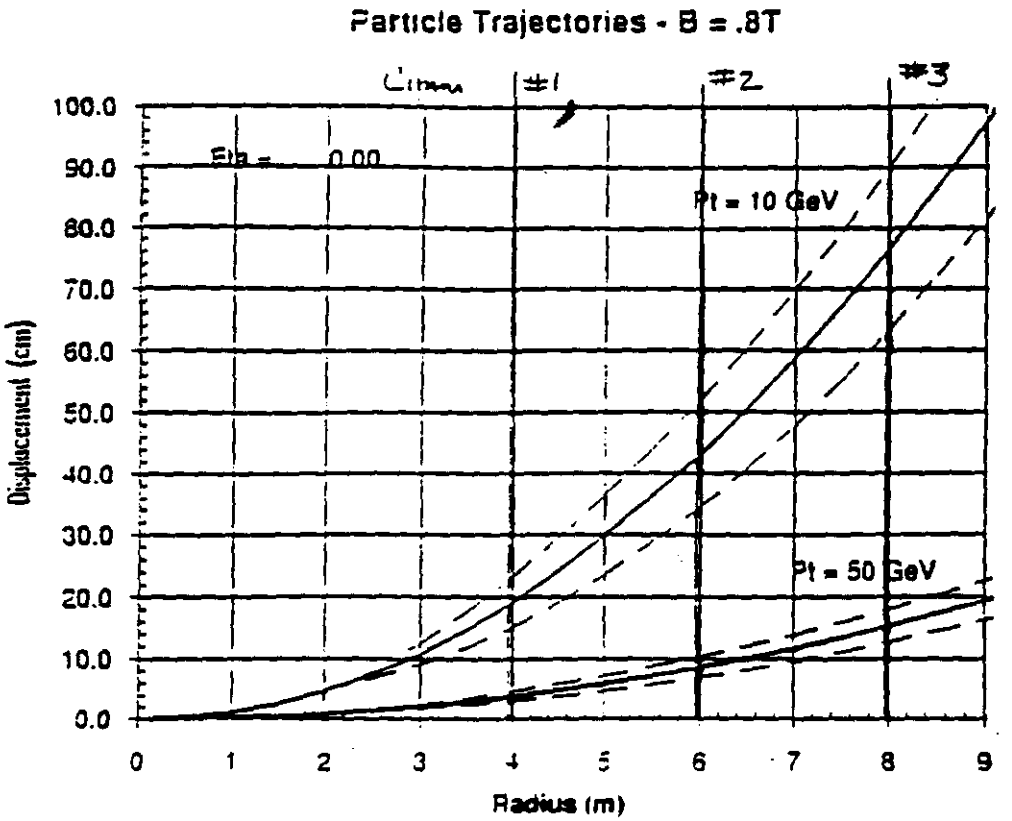
$\frac{\varepsilon}{2} < 16$ NANOSECONDS

$R = 2\text{CM} = 20{,}000$ MICRONS

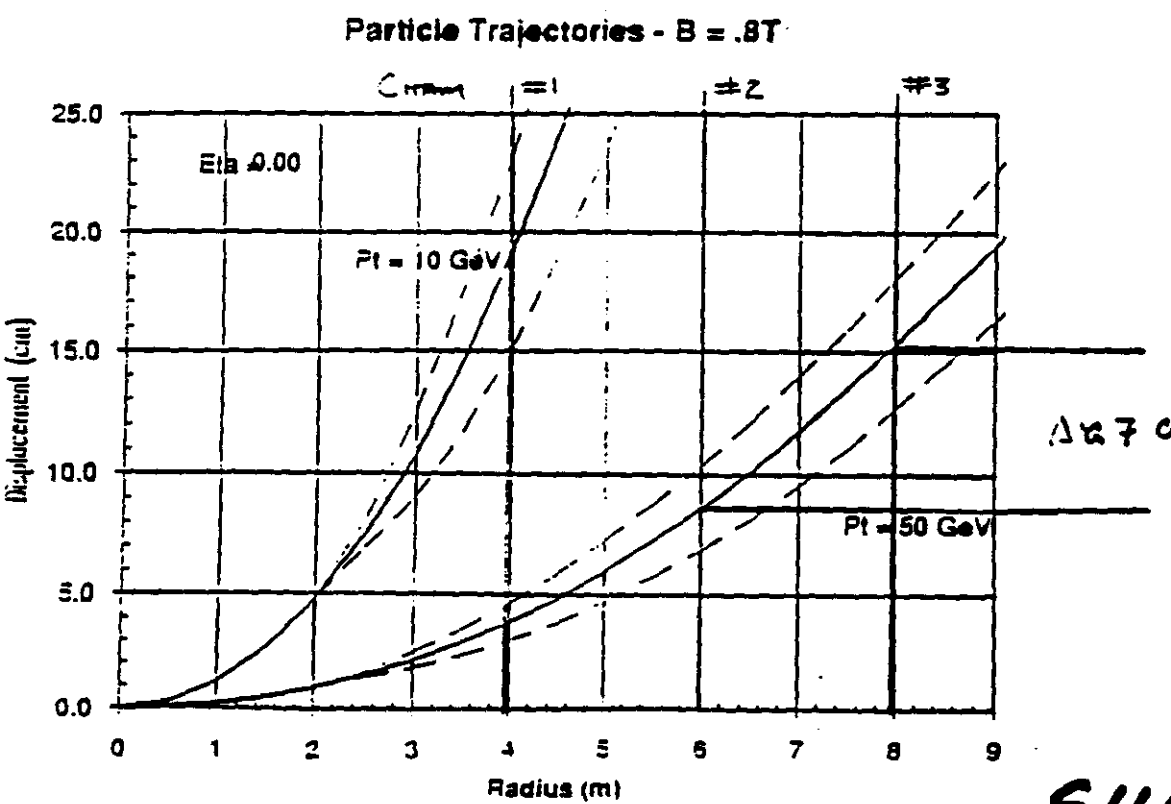
DRIFT VELOCITY = 50 MICRONS/NANOSECOND

$\theta \doteq 2.6$ DEGREES

ONE SECTOR SUBTENDS $\pm 10^\circ$

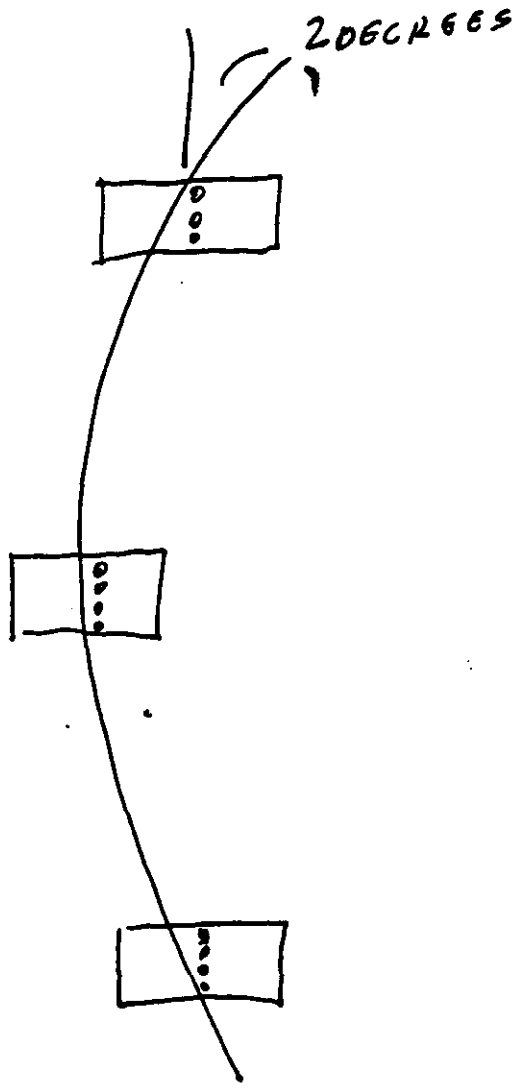


$\eta = 0$ trajectories.
(90°)



$\Delta x \approx 7$ cm.

SHAEVITZ



TRACK CAN HAVE A TWO DEGREE ENTRANCE DUE TO MAGNETIC FIELD

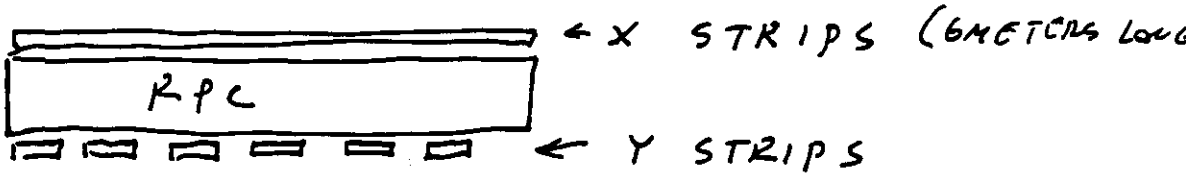
PARALLEL TO CAT, DELTA RAYS ARE A REAL PROBLEM.

4 RPC FOR Z COORDINATE DETERMINATION

BY USING 9mm STRIPS A RESOLUTION OF LESS THAN ONE MILLIMETER HAS BEEN ACHIEVED BY THE STANDARD CHARGE DISTRIBUTION TECHNIQUE. IT SEEMS POSSIBLE THAT 200-300 MICRONS CAN BE ACHIEVED. THIS WOULD MEAN RPCs COULD BE USED IN PLACE OF "COURSE" WIRES

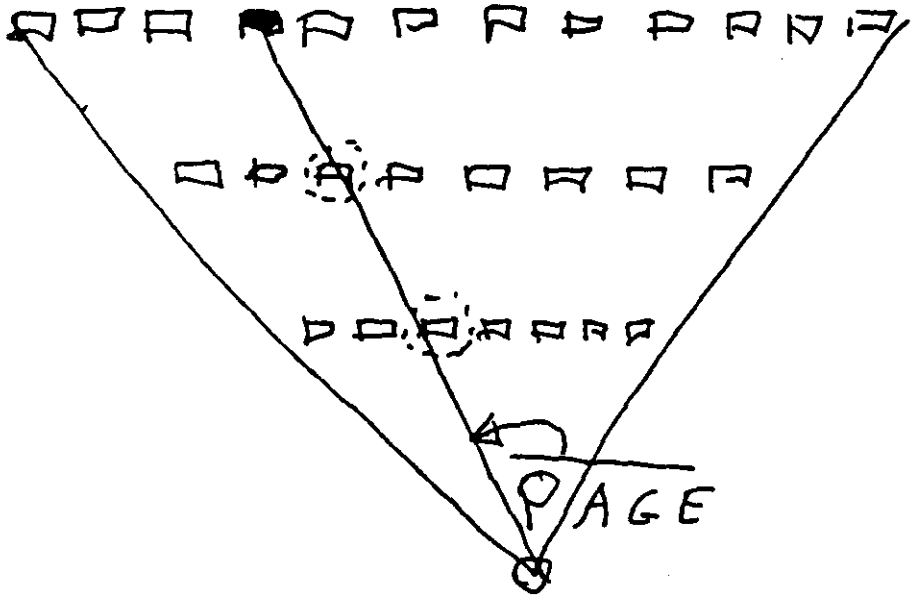
5. RPC FOR TRIGGER

WE PROPOSE A TWO DIMENTIONAL RPC SYSTEM FOR THE MUON TRIGGER.



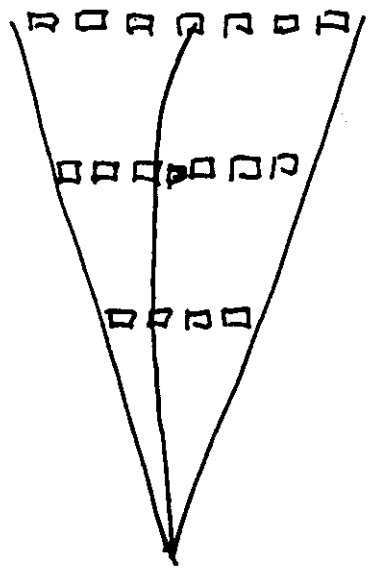
WE NOTE FROM THE L^* EOI PAGE 37 THE Y STRIPS RANGE IN LENGTH FROM 1.5 METER TO 3.3 METERS. THESE STRIPS ARE SHORT ENOUGH TO DETERMINE THE CORRECT BEAM CROSSING FOR THE EVENT THAT CREATES THE TRIGGER.

THE PROPOSED TRIGGER TECHNIQUE EXAMINES THE NON BEND PLANE FOR A THREE FOLD COINCIDENCE OF THE Y STRIPS, ONE IN EACH LAYER. THIS IS MADE SIMPLE BY USING A PAGE TECHNIQUE, WHERE A PAGE IS DEFINED BY OUTERMOST Y STRIP STRUCK AND THE INTERACTION POINT.



INTERACTION POINT

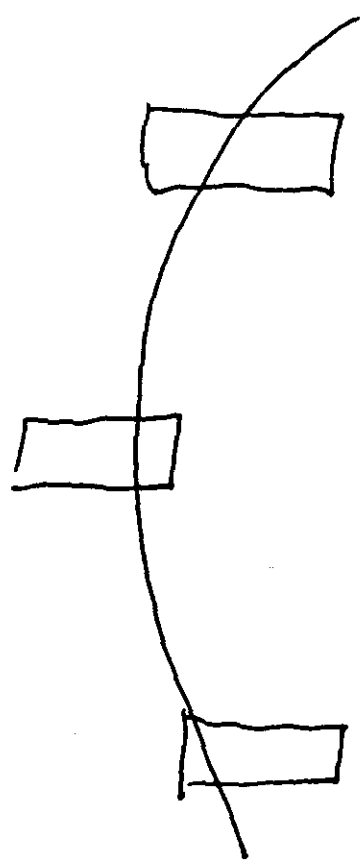
IN THAT PAGE ONE THEN LOOKS FOR A THREE FOLD X STRIP COINCIDENCE ONE IN EACH LAYER



THE SAGITTA IN THIS PAGE MUST BE LESS THAT THE DESIRED MOMENTUM CUT. WITH THE CENTIMETER STRIPS YOU CAN MAKE A CUT AT 50 GEV/c.

6. RPC FOR SAGITTA MEASUREMENT

IF ONE CAN DEMONSTRATE 100 – 200 MICRON PRECISION FOR RPC SPATIAL MEASUREMENT, ONE IS TEMPTED TO CONCIDER THEM AS THE ONLY MUON TECHNIQUE. HOWEVER DUE TO THE RELATIVELY LARGE MASS, THIS NEEDS MORE CAREFUL STUDY.



THE MOST DOUBTFUL SITUATION IS FOR THE CENTER POSITION. MASS AT THIS POINT IS HARMFUL.

Resistive Plate Counter R&D at LLNL -

Elden Ables, Richard Bionta, Dan Makoweicki, Craig Wuest

- RPC R&D at LLNL is taking advantage of an extremely capable Chemistry and Materials Science Division.
  - We have expertise in coating a variety of dissimilar materials using a number of different technologies: e.g. sputtering of As on Pu.
  - We have identified a resistive soda-lime glass as a candidate for RPC plates (in place of the carbon-painted phenolic).
  - We will build a 25 x 25 cm^2 RPC in the first part of the program, based on the work of Cardarelli, et al., NIM A263 (1988).
  - Discussions with I. Pless of MIT have been initiated and a joint effort to develop RPC's is envisioned
  - Larger 1 x 1 m^2 RPC's in the future.

RPC Coatings:

- LLNL has sputtering systems for a number of different materials.
- We have made resistive anodes for position-sensitive detectors using sputtered films of 35% Cr - 65% SiO
  100 kΩ → >1 MΩ/□
- Can also sputter carbon.
- Example of process cost: LSHC μgaps
  - We have found manufacturer's to coat Au and Y on borosilicate glass plates.
  - 6,000 m^2 of 0.1 μm Y (8×10^5 pieces)

    ⟹ \$67/m^2

    6,000 m^2 of 200 Å Au "

    ⟹ \$54/m^2

7. R AND D PROGRAM

TESTS

MIT – COSMIC RAYS
BATES – ELECTRONS (PION?)
MIT REACTOR – NEUTRONS

REQUESTING $ 395 K

MECHANICS MIT	20K
MECHANICS BATES	15K
MECHANICS REACTOR	5 K
RPC CONSTRUCTION	20 K
ELECTRONICS FOR RPC	20 K
TDC SYSTEM - DRIFT CHAMBERS	30 K
ADC SYSTEM - SPATIAL RESOLUTION RPC	30 K
D.C. CONSTRUCTION	30 K
S.C. CONSTRUCTION	10 K
READ OUT STRIPS	20 K
GAS SYSTEMS	10 K
DAQ	15 K
FULL TIME TECH	75 K
1/2 TIME ENG	50 K
TRAVEL (ACC - MEETING - ETC)	30 K

1. Maximum achievable Time resolution
2. Studies to improve spatial resolution
3. Gas choices with emphasis on nonflammable mixtures
4. Noise
5. Aging and its effects.
6. Performance in high charge particle flux environment
7. Performance in high neutron radiation environment
8. Choice of readout electronics
9. Choice of electronics to generate fast trigger
10. Collaborative work with other groups (Daq/Trigger and Muon MonteCarlo) with a view to a final large scale design.

THE TEST FACILITY

The Test Facility at MIT will consist of

1. A Test Stand to set up a Muon Telescope
2. A three component Gas system
3. Appropriate Readout Electronics
4. A Data Acquisition and Data Analysis system
5. Other testing hardware including a Lecroy Oscilloscpe

This system will be put together in such a manner that it could be easily transported to an accelerator environment for beamline tests.

COLLABORATIVE WORK WITH LLNL

Collaborative work with LLNL will include tests of new RPC prototypes made at LLNL at the MIT facility and mutual feedback of information necessary to optimise various performance criteria. A meeting to discuss the collaborative effort has been scheduled for the last week in August.

COSTS

The heart of the Test Facility will consist of a Muon Telescope with three layers of scintillator for triggering, six layers of Drift chambers for accurate position determination and one or more Test RPC layers in between. We estimate the cost of constructing and operating this system to be $395K. This includes the acquisition of all necessary hardware ($240K), one full time technician ($75K), one half time engineer ($50K) and travel ($30K).

---

6 CONCLUSIONS

AS IN THE L* EOI, RPC SEEM AN EXCELLENT CHOICE FOR THE FIRST LEVEL TRIGGER.

IT NOW APPEARS THEY CAN REPLACE THE "COURSE" WIRES FOR TRANSVERSE MEASUREMENT.

THE PAGING TRIGGER TECHNIQUE IS EASILY APPLIED AND will LOCATE THE CROSSING BUNCH. DELTA RAYS ARE NO PROBLEM.

THE PRICE OF 4000 m² COULD BE AS LOW AS $800,000 FOR THE MECHANICAL HARDWARE AND THE SYSTEM will NEED NO PRE AMPLIFIERS

Talk by Scott Whitaker

on Interpolating Pad Chambers

PAD CHAMBERS FOR MUON MEASUREMENT IN GEM

MUON GROUP MEETING

Boston University

23 August 1991

Scott Whitaker

Chamber development work done by BNL team, including

Vinnie Polychronakos
Bo Yu
Veljko Radeka
Ed Obrien

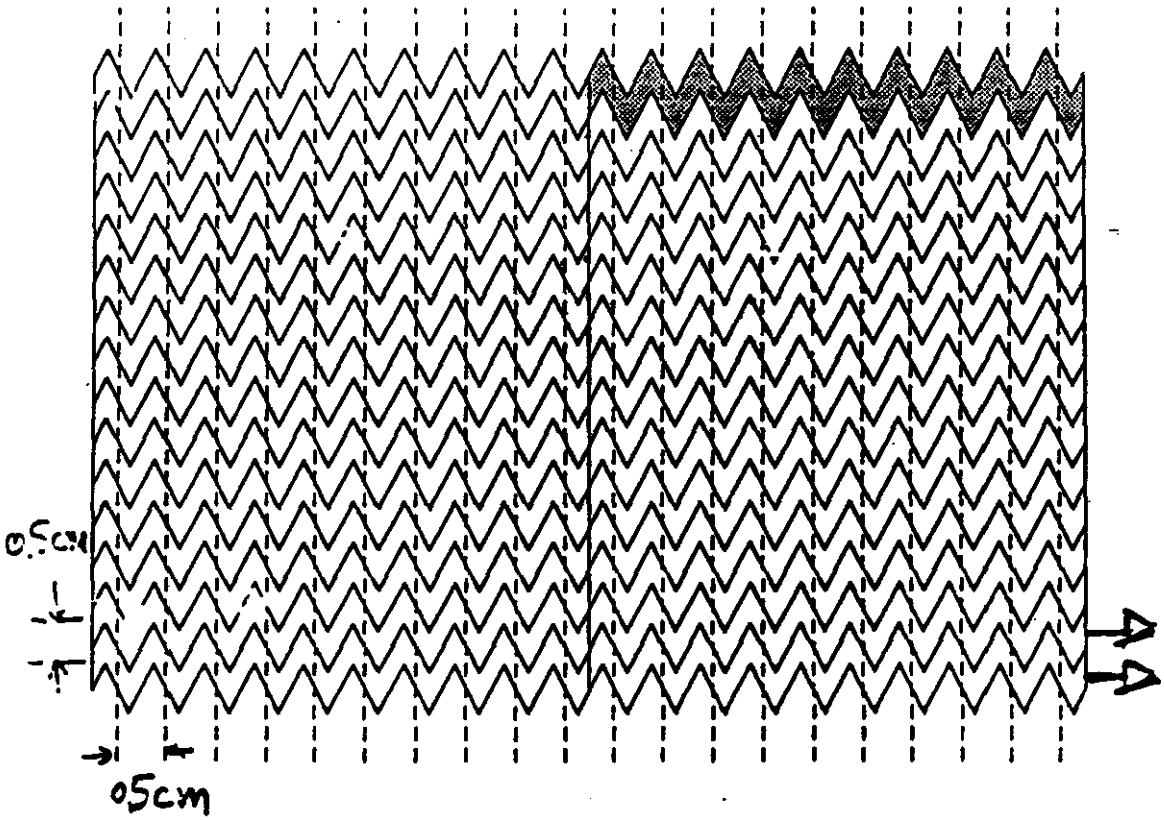
Engineering for GEM application

Vinnie Polychronakos
Charlie Grinnell
Frank Nimblett

- Cathode pad chambers – integrated technology for
  - bend plane measurement
  - theta measurement
  - triggering

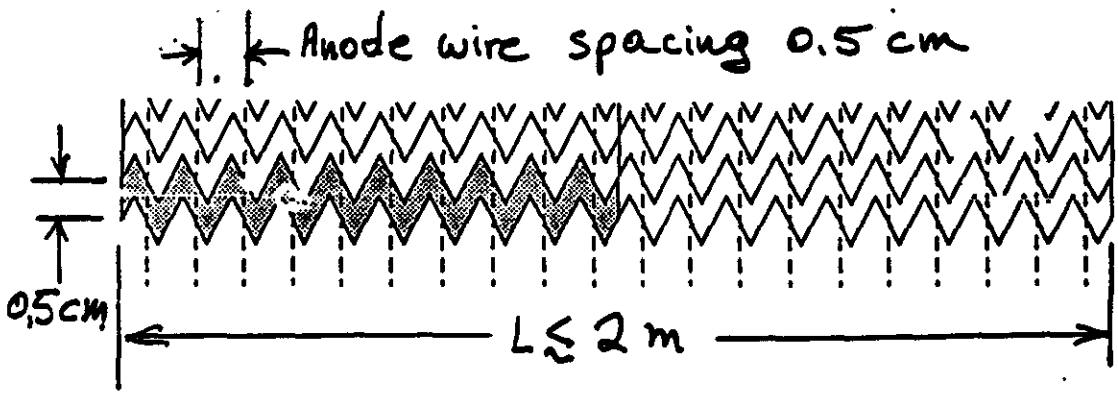
- Possible realization for GEM
  - mechanical layout
  - electronics
  - advantages and disadvantages

- R&D to test the concept


0.5cm
0.5cm

Pad Size

1. Interpolation direction
   - Required Interpolation Preecision ×100
2. Transverse to the interpolation direction
   - Occupancy
   - Channel count
   - Total pad capacitance (≈100 pf)
   - Shaping time (τ_m)



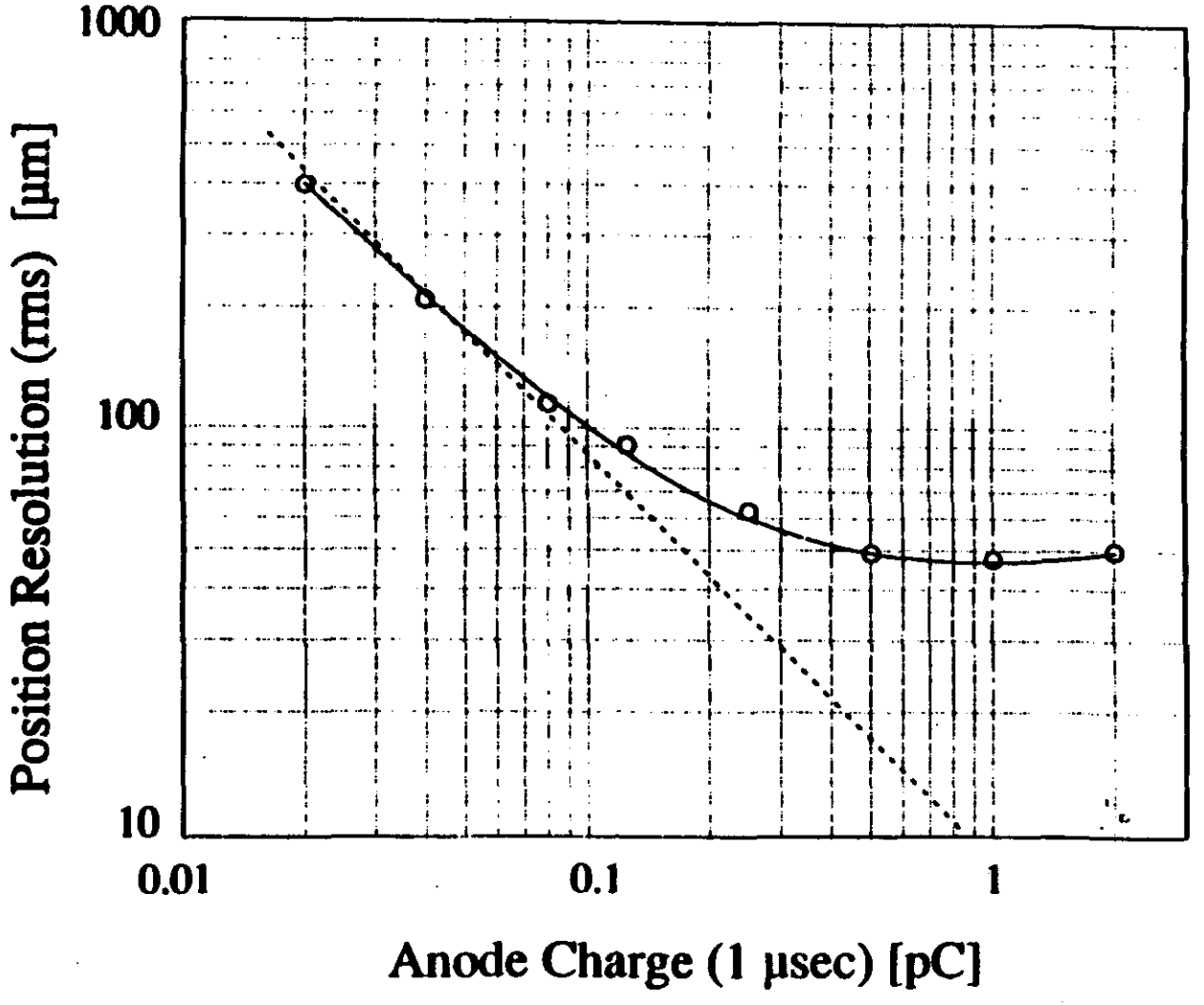
- Inter-chevron capacitance dominates
  $C = 0.2 - 0.3$ pf/cm

<u>Example:</u>
$\mathcal{L} = 10^{33}$, Max. rate/pad 5 Hz, $\tau_m = 1\,\mu s$

- $|\eta| = 2.5$ $L = 10$ cm Limited by occupancy
- $|\eta| < 1.5$ $L = 1.5 - 2$ m Limited by C_D

Position Resolution vs. Anode Charge
for a Single Chevron Cathode

(5.4 keV X-rays, 12mm readout spacing, 50% Ar + 50% C_2H_6 gas mixture)



Resolution

Interpolation error $\approx$ 1% of pad spacing, d
100μm achieved with $d = 1.2cm$

$$\sigma \propto \frac{\overline{ENC}}{Q}$$

$$\overline{ENC}^2 = 16\frac{2}{3}kTC_D(\frac{\tau_A}{\tau_m})$$

$$\tau_A = \frac{C_{GS}}{g_m}$$

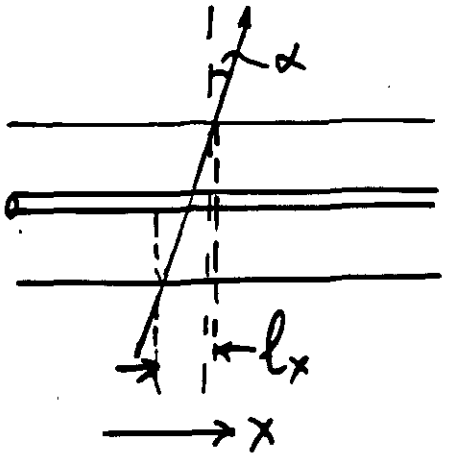
Optimum when $C_D = C_{GS}$

$$\boxed{\overline{ENC}^2 = 16\frac{2}{3g_m}kTC_D^2(\frac{1}{\tau_m})}$$

Aim at $\overline{ENC} \simeq$1000 e

Then gas gain $\approx 1 - 2 \times 10^4$

Effect of the angle of incidence



$\frac{\sigma_x}{\ell_x} \approx 0.10$
(V. Radeka, B. Yu, BNL)
(W. Blum, CERN Workshop)

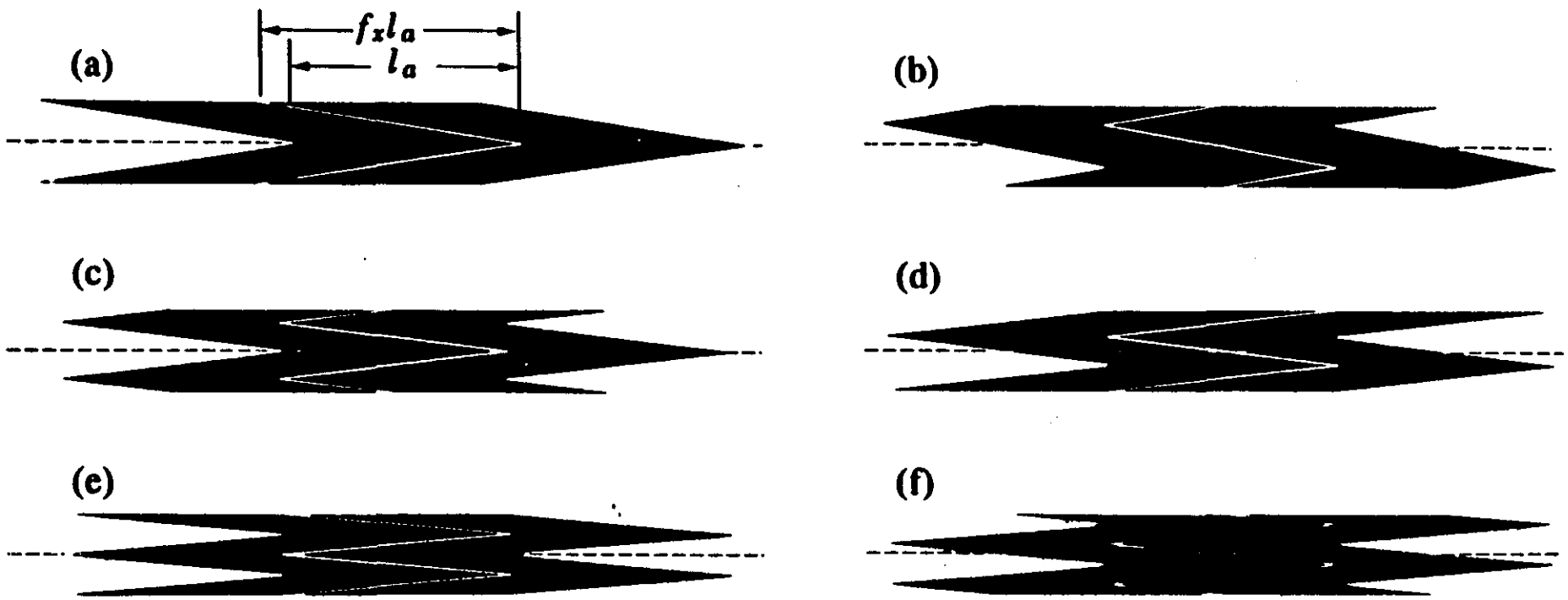
$$\frac{\sigma_x}{\ell_x} = \frac{d \tan\alpha}{\sqrt{12}\,\sqrt{N_{eff}}}\,\ell_x^{-1} \qquad d = 0.5\,\text{cm} \qquad N_{eff} = 3$$

$$= 0.08$$

Assuming $\sigma_x \approx 50\mu m$
$\theta_{max} \approx 4.5\,\text{deg} \Longrightarrow$ 40, 9deg segments (Tessaracondahedron)

$$\begin{array}{ll} R = 4m & L_{R\phi} = 0.6m \\ R = 6.5m & L_{R\phi} = 1.0m \\ R = 9m & L_{R\phi} = 1.4m \end{array}$$

- Largest chamber $2\times1.5\ m^2$
- Chamber already exisiting in BNL E814, $0.5\times2m^2$
- Precision determined by lithography of cathode planes.
- No extraordinary precision in placement of anode wires required.

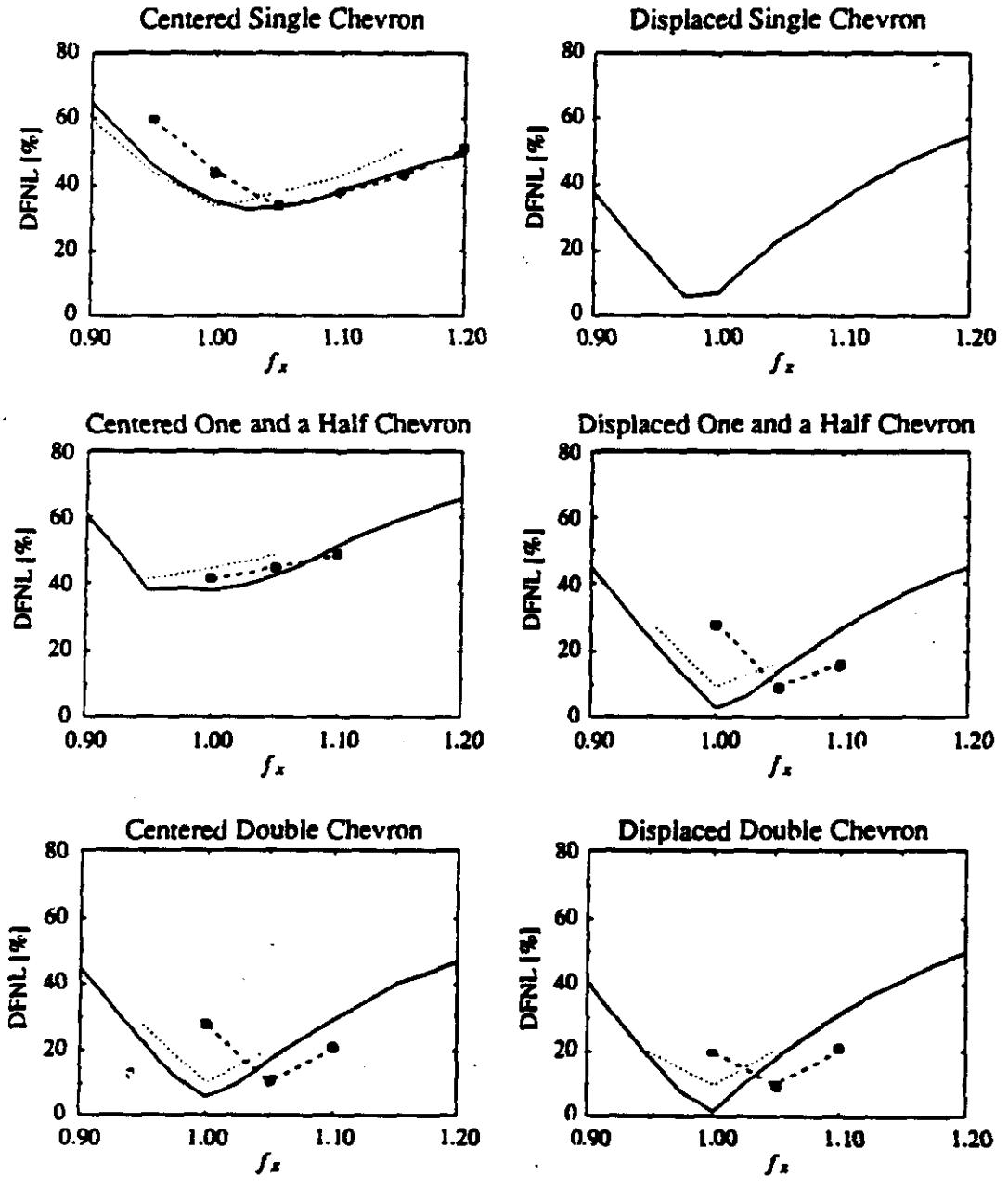


a) Centered single chevron
b) Displaced single chevron
c) Centered one and a half chevron
d) Displaced one and half chevron
e) Centered double chevron
e) Displaced double chevron

Dash line indicates anode wire position.

DFNL vs. f_x for Various Chevron Patterns

(Gap width = 75 μm)



Theoretical prediction

Experimental result

Experimental results displaced by f_x =0.05

MECHANICAL LAYOUT CONCEPT

4 chambers in an integrated package

Chambers to 1.5 m (phi) x 2 m (z or r) -- longer possible by piecing

Hexcell	-- 25 mm thick	5 x
Circuit board	20 -- 100 mils	10 x

deflections for center of 4 ft x 8 ft laminate < 0.1 mm (C. Grinnell)

Alignment targets integral to cathode strip structure

5 mm gas gaps

Anode wires 2.5 mm pitch

Center supports: 50 gm tension

Ganged by 20 for theta measurement

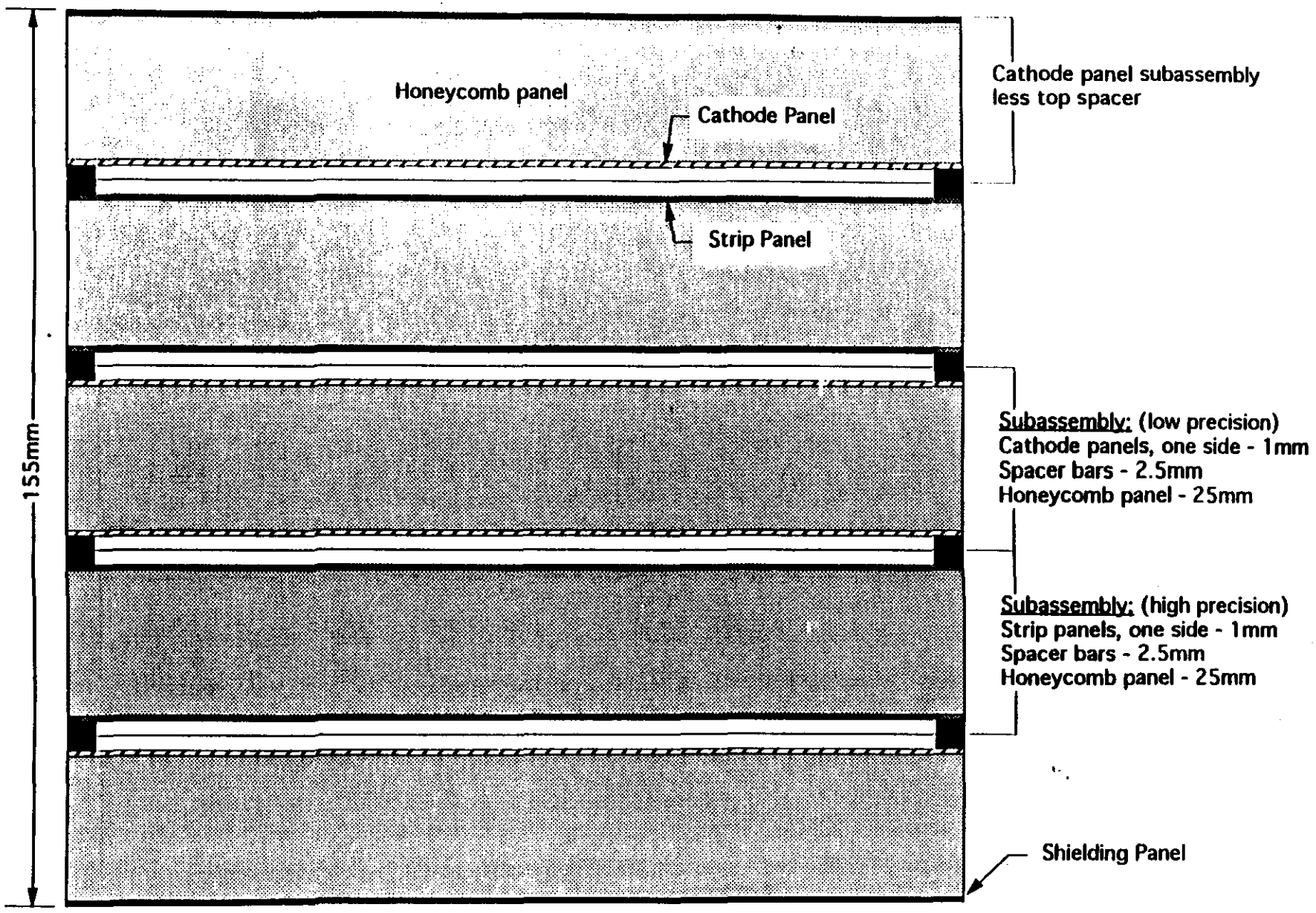
Weight of 4-gap package 25 Kg/sqm (modeled as 10 x 1.5 mil Cu + 1 mm G-10 boards)

Thickness for super layer of 4 chambers < 8% X0

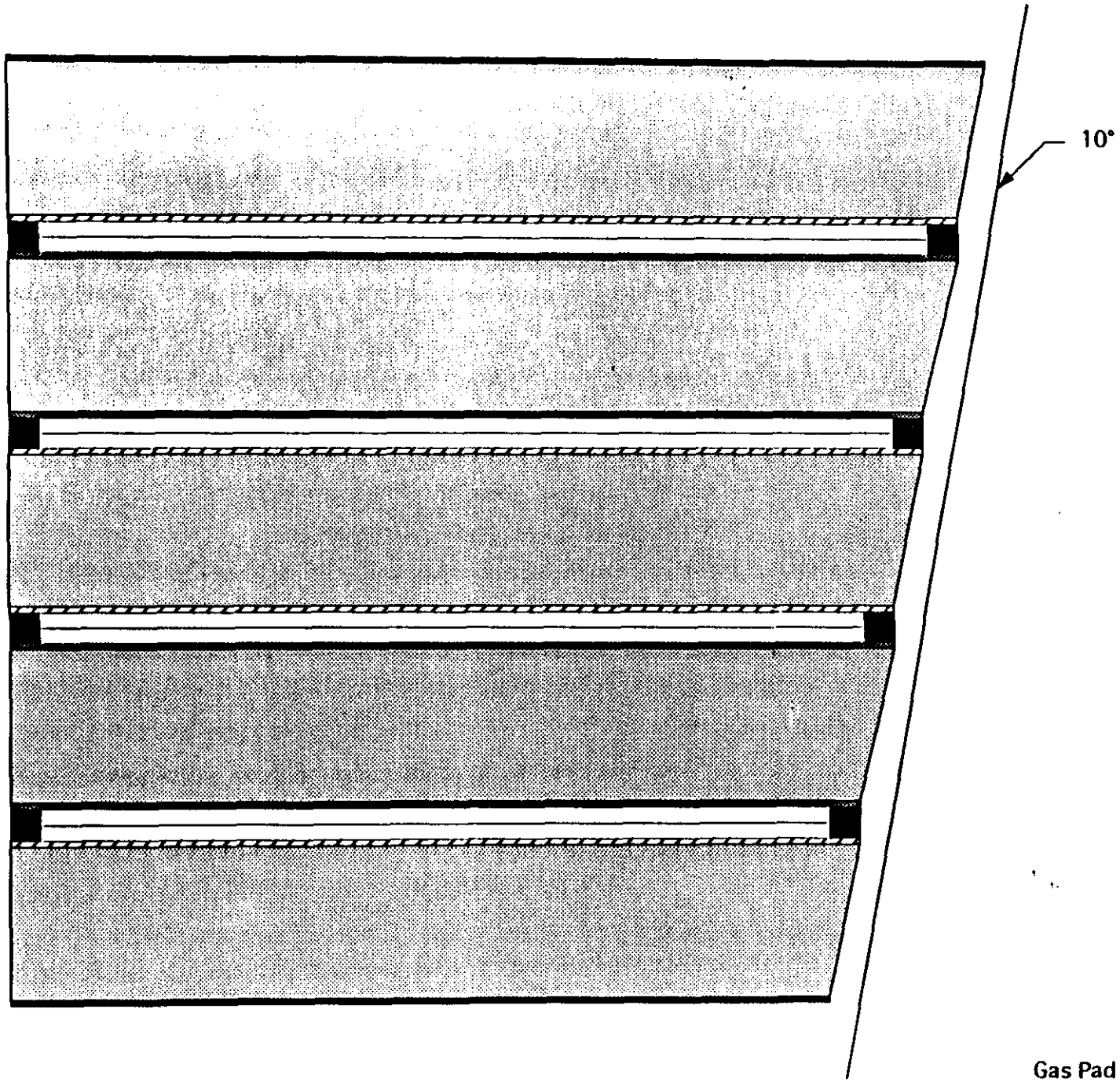
Electronics mounted on cathode boards -- full readout chain + trigger processor (?)

2cm + 5 cm allowance on sides for wire termination, theta electronics

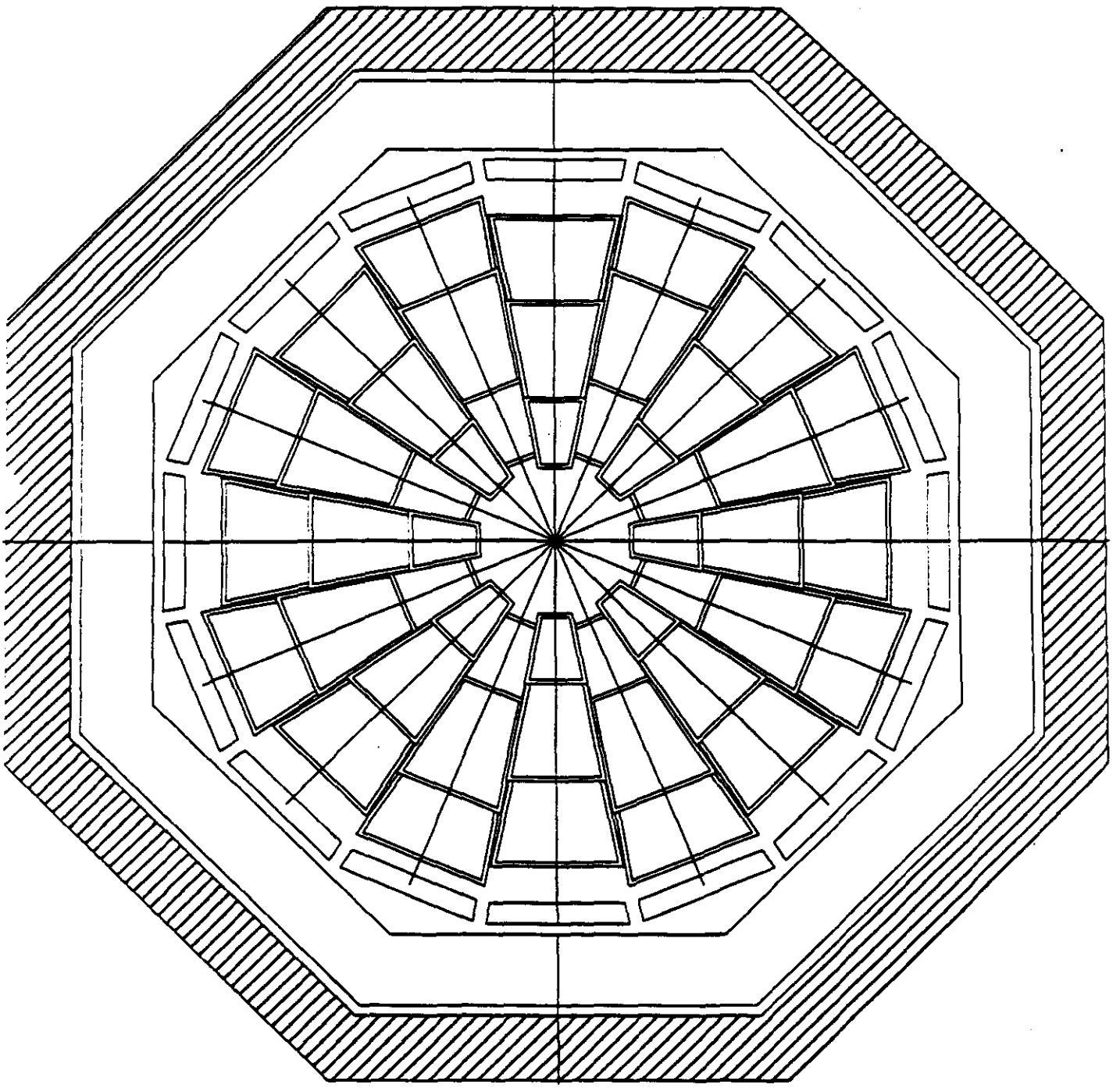
20 cm on one end for strip readout



Gas Pad Chambers Study.2
C. Grinnell 09.08.91 page 1/2



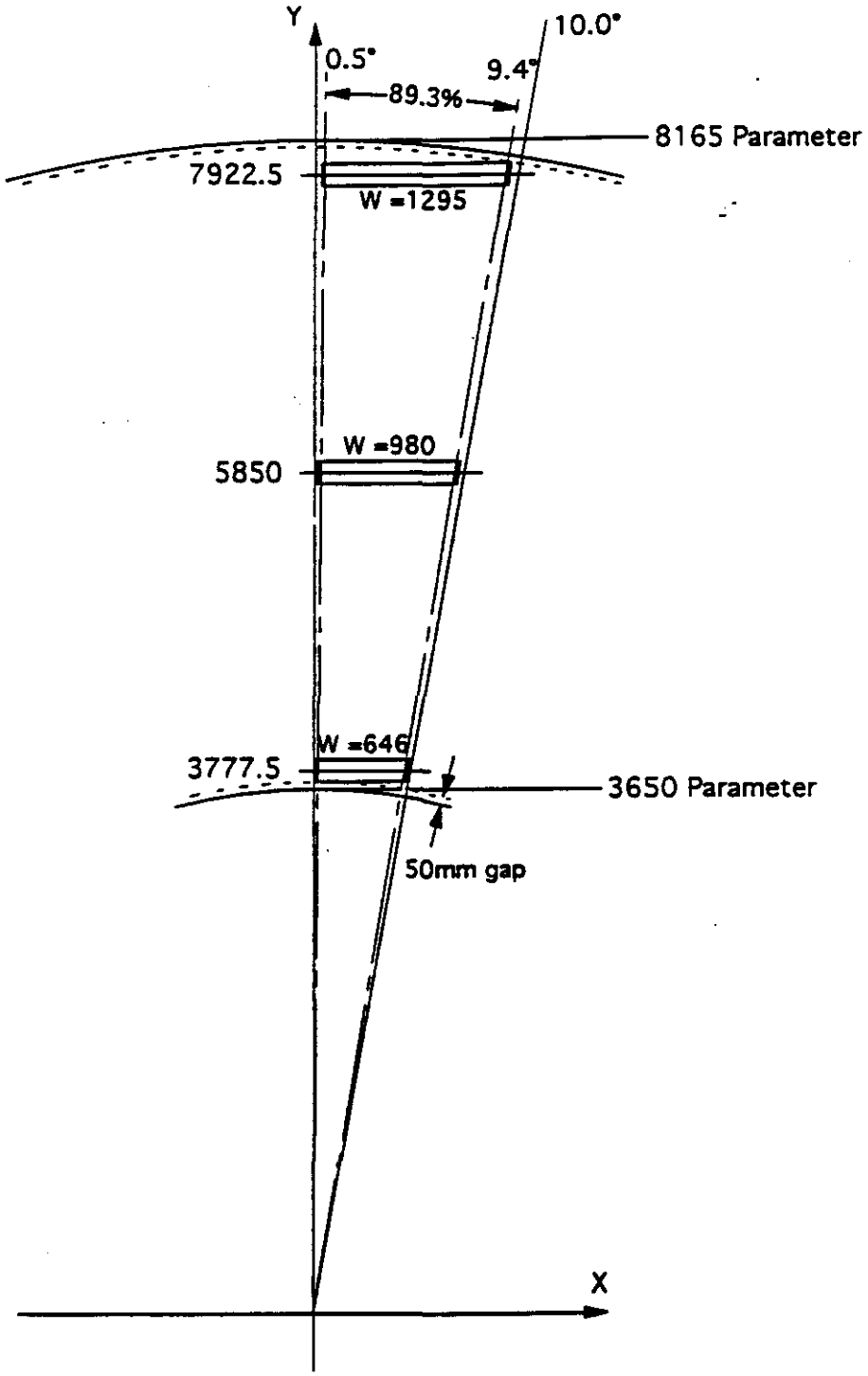
Gas Pad Chambers Study.2
C. Grinnell 09.08.91 page 2/2



L* 20MW Magnet Version/4

Muon Spectrometer Volume

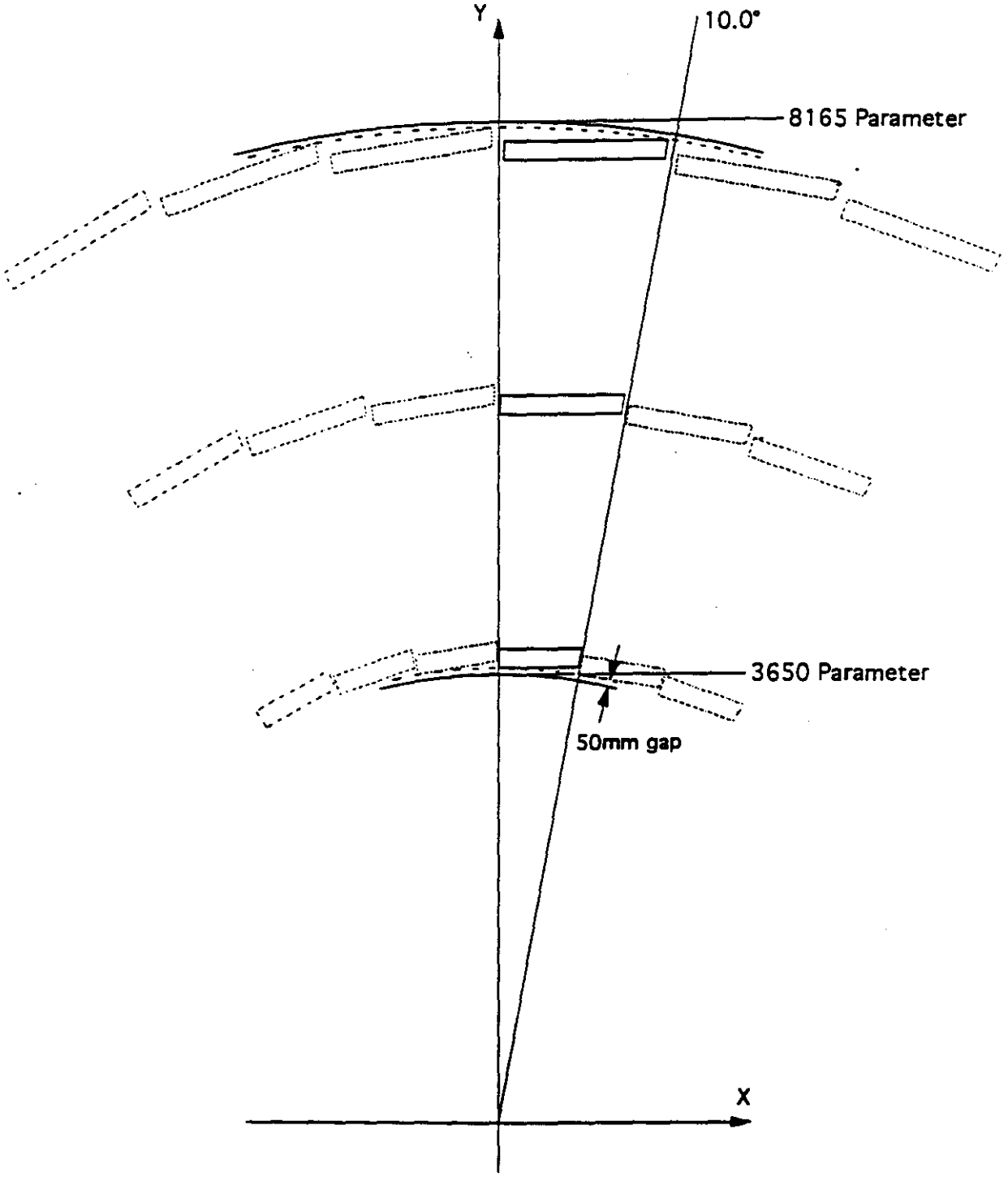
C Grinnell
scale 1 100
version 4 5 14.02.90
from 20MW/4 13 10 89



Gas Pad Muon System

Central Region Section

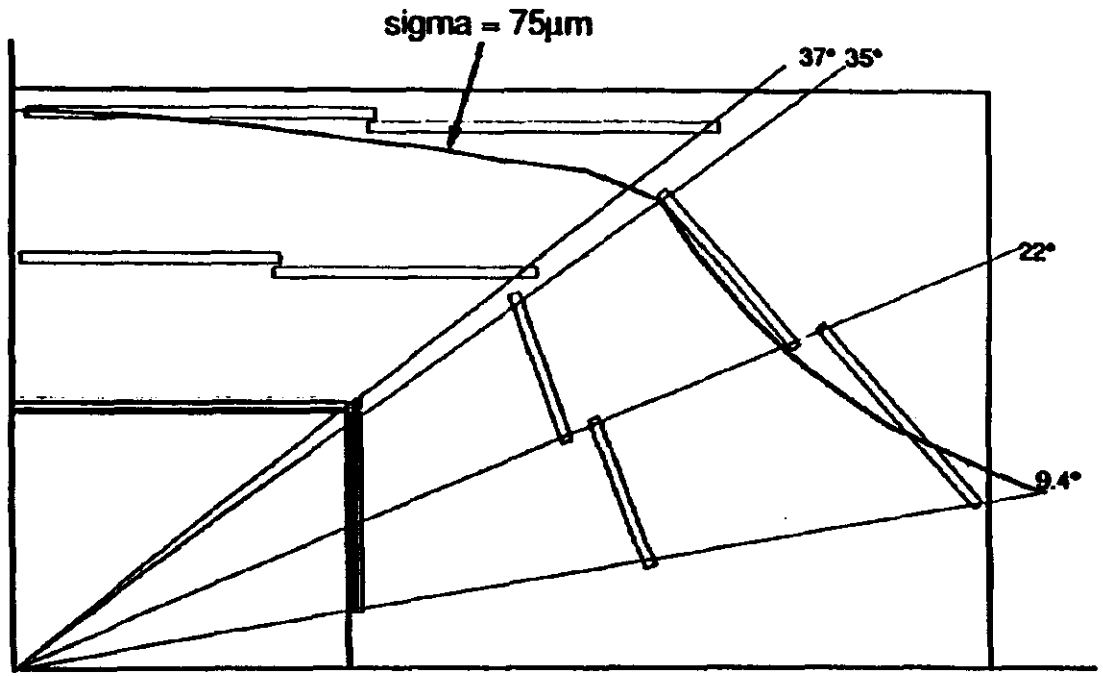
C. Grinnell - Study.1
09.08.91
Scale 1:50



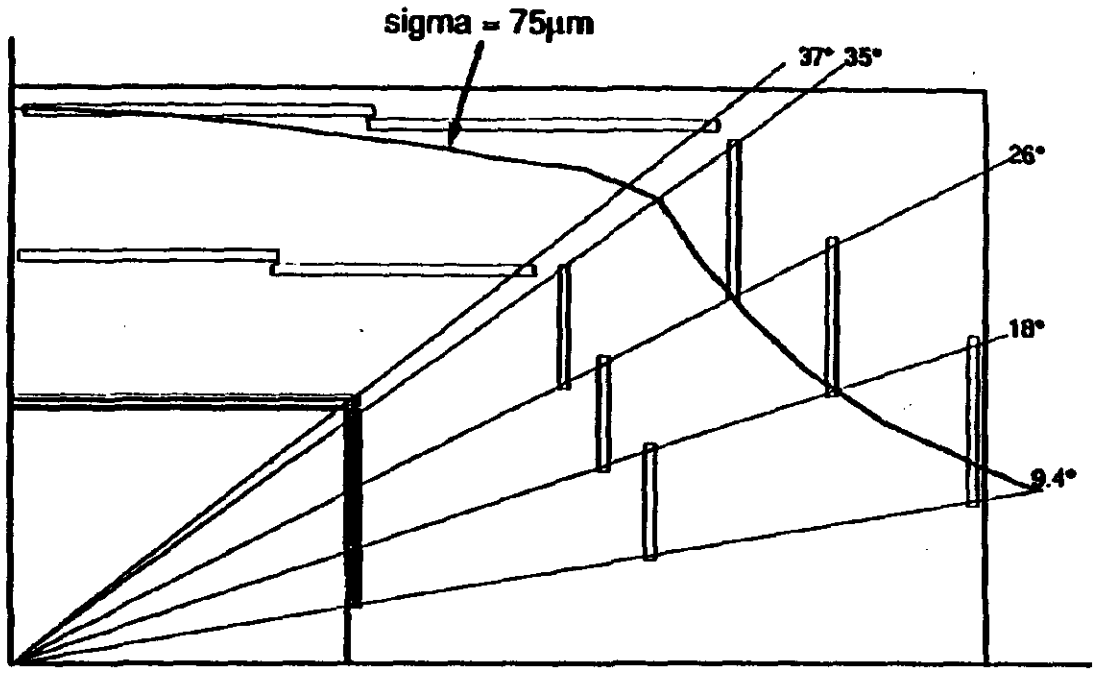
Gas Pad Muon System

Central Region Section

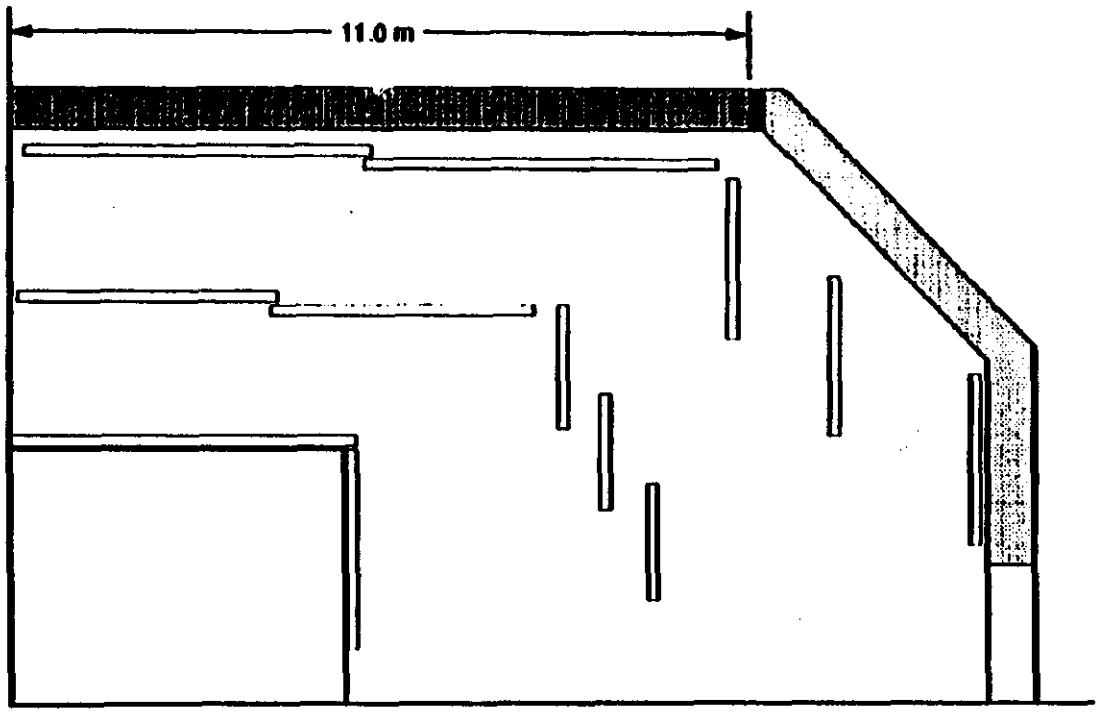
C. Grinnell - Study.1
09.08.91
Scale 1:50



Gas Pad Layout.4
CG - 19.08.91
1:100

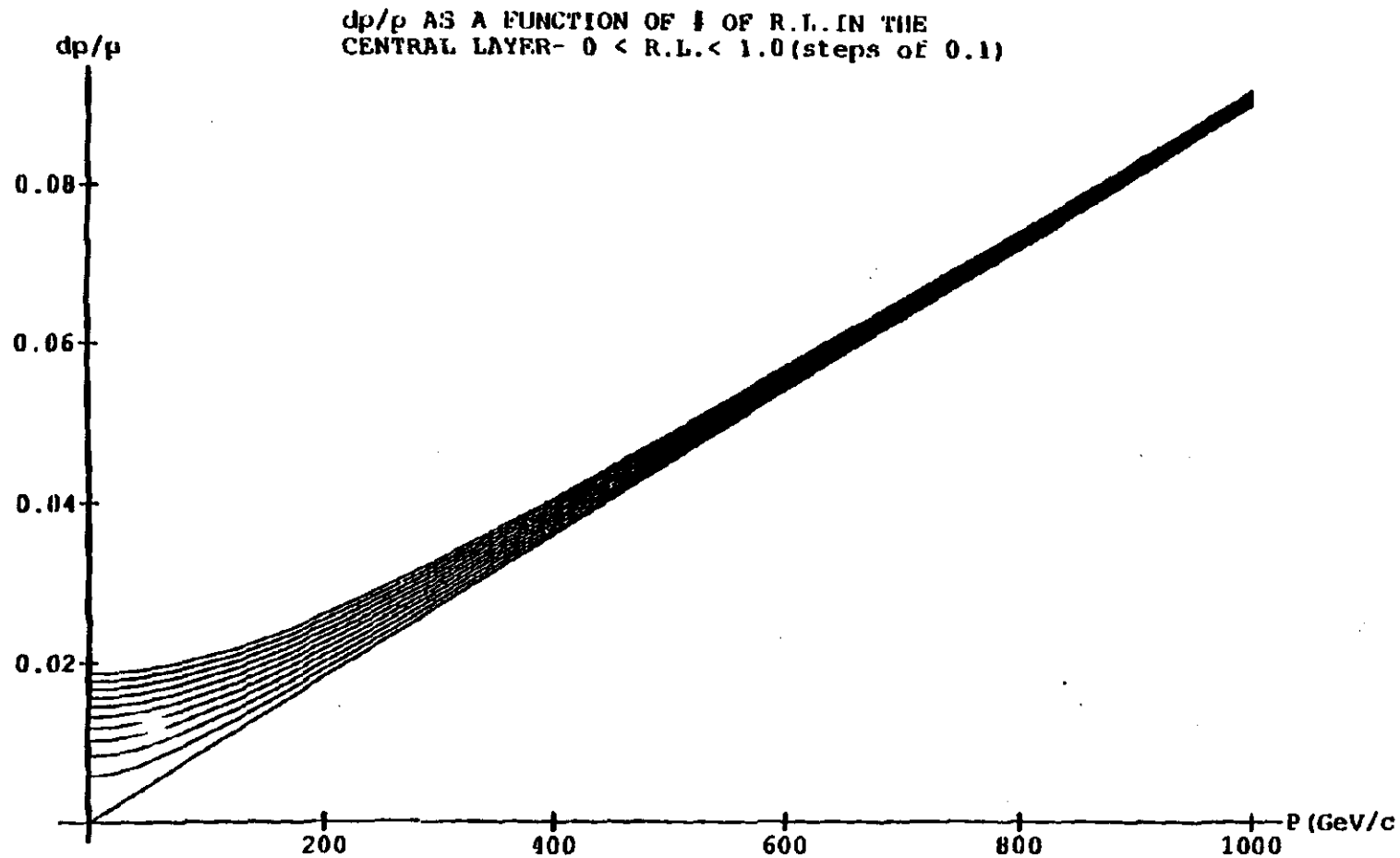


Gas Pad Layout.5
CG - 19.08.91
1:100

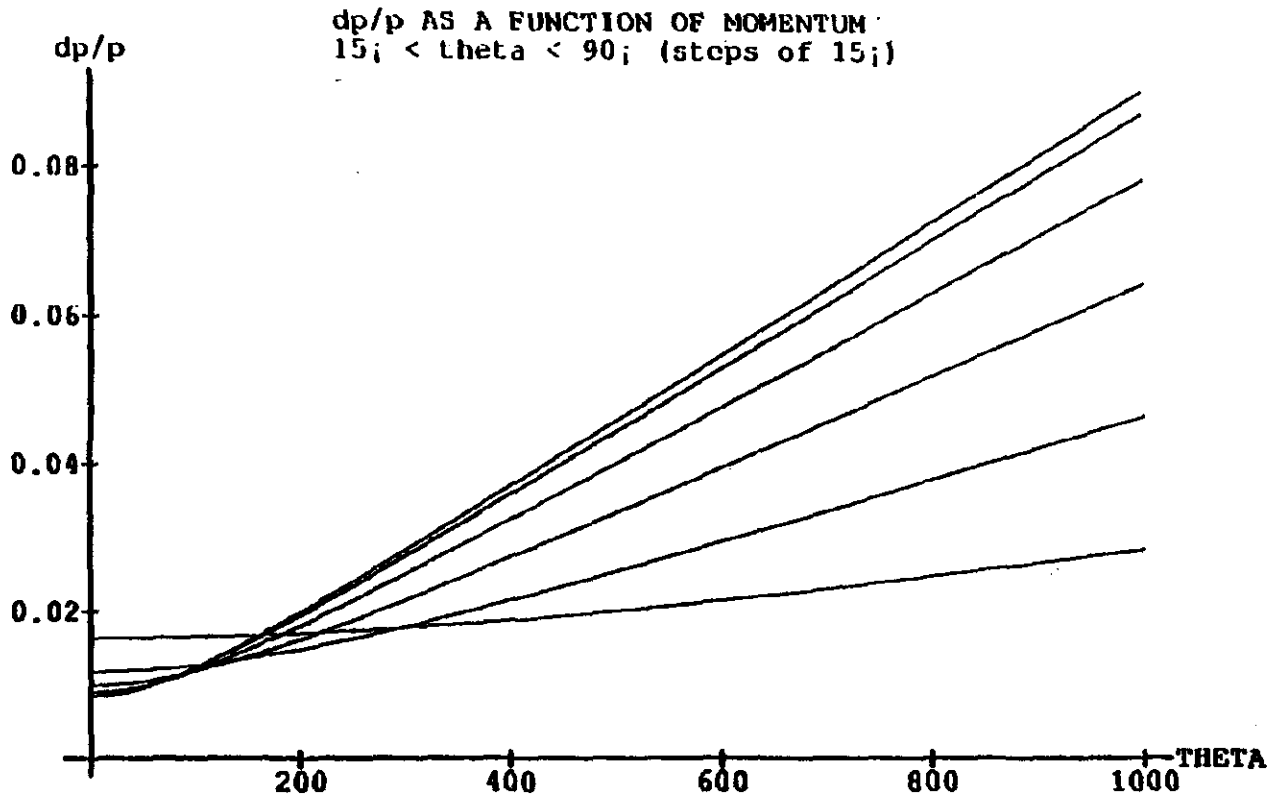


Gas Pad Layout.5
CG - 19.08.91
1:100

PI_SAG_COMP#9.m

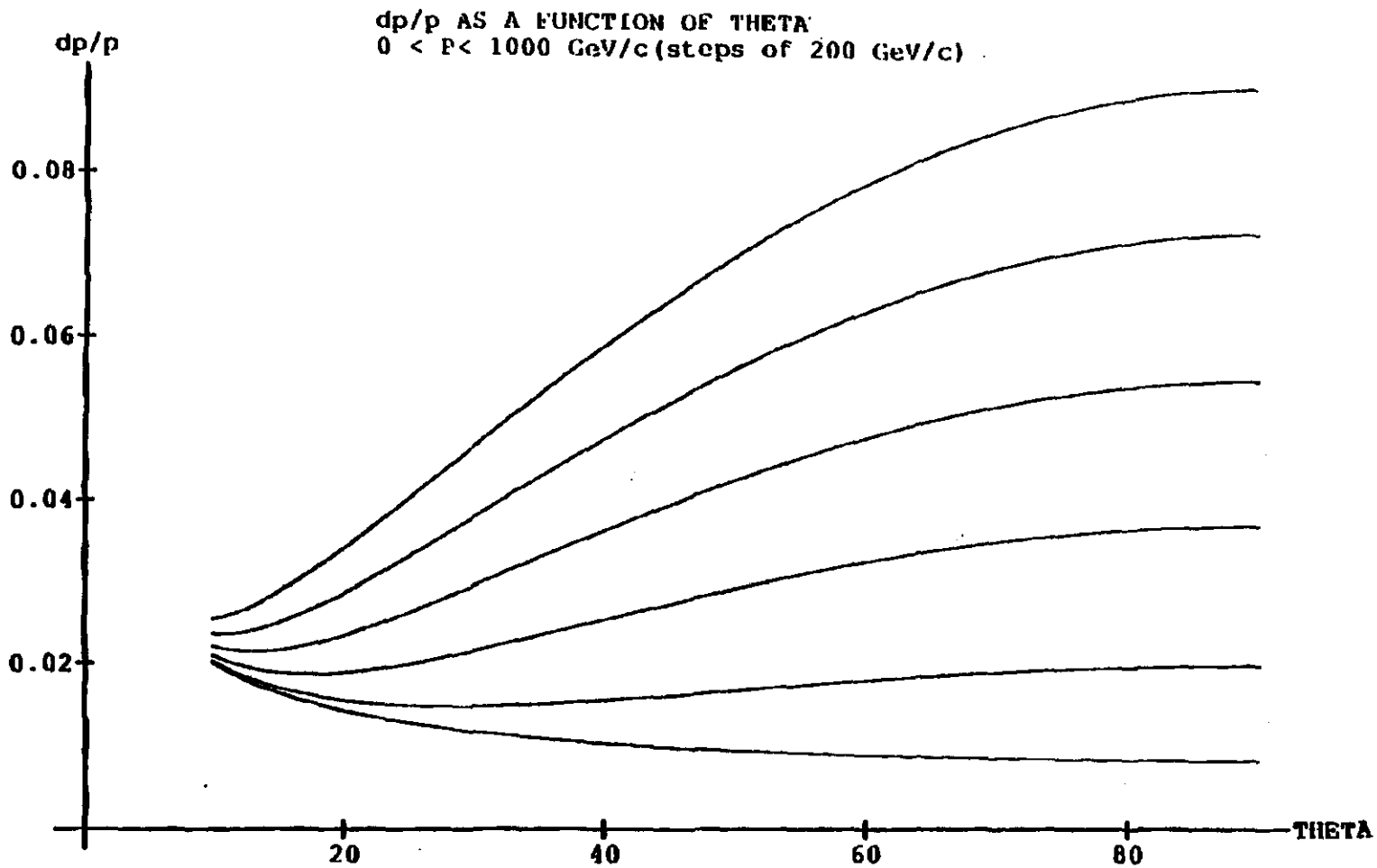


PI_SAG_COMP#9.m



mrl μ in
central layer.
= 0.2

PI_SAG_COMP#9.m



For Example...

Chevron chambers for BNL experiment 814 Ed Obrien

chambers 0.5 m x 2 m

5 mm gap

3 layer pc board for cathode pads

.100 in thick

cathode plane, ground plane, signal routing -- plated through holes

precision < 50 microns

photo technology

humidity, temperature control during mfg

$10,000 for order of 3

1/4 " hexcell lamination

second side -- 8 mils prepreg

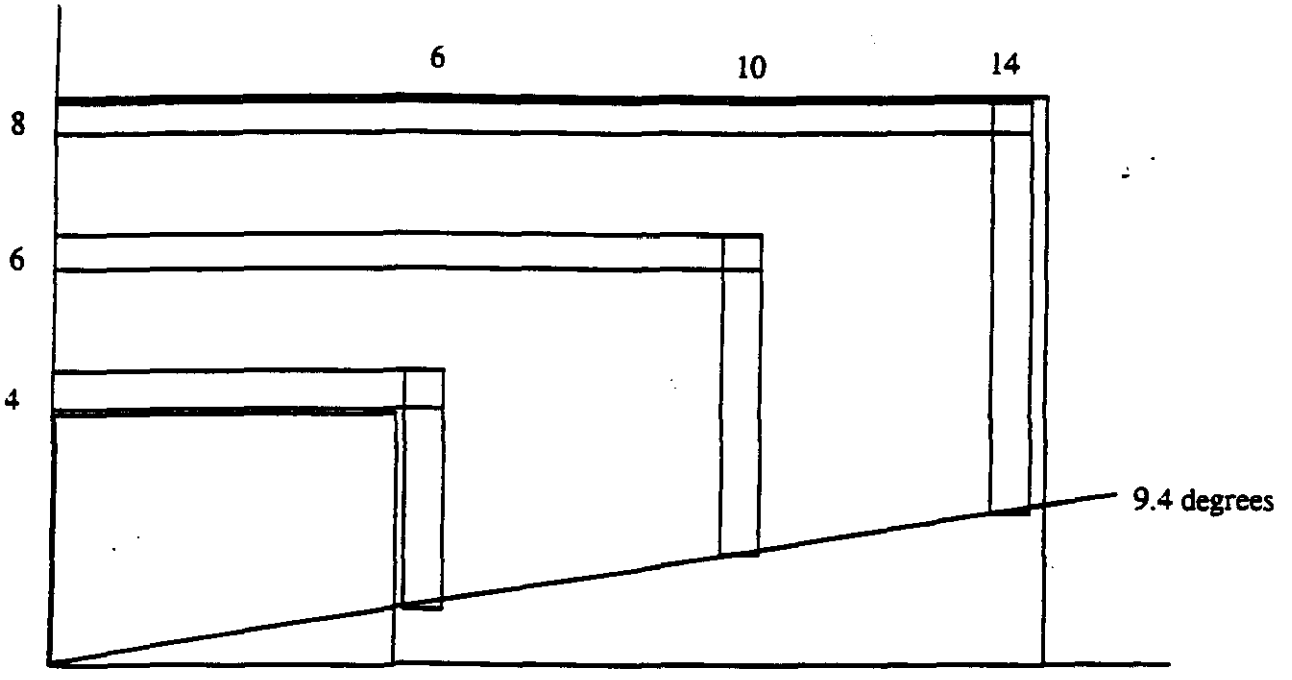
flat to < 5 mils

Performance in Si ion beam as designed

< 5% of pad size --- limited by dynamic range requirements

CHANNEL COUNTING

Model used -- not the most efficient...



	Bend plane	Theta
BARREL	40-fold symmetry strips 5 mm (r-phi) x 2 m (z) capacitance-limited	wires run r-phi 2.5 mm pitch ganged by 20 --> 5 cm hodoscope
	4, 4, 3 chambers	2, 2, 2 chambers instrumented
	844K channels	96K channels
ENDCAPS	20-fold symmetry strips 5--6 mm (phi) x .23--2.0 m (r) occupancy /capacitance limited	wires run r-phi 2.5 mm pitch ganged by 20
	4, 4, 3 chambers	2, 2, 2 chambers instrumented
	occupancy < 10 Hz : 231K channels	21K channels
	occupancy < 5 Hz : 397K channels	

Barrel Channel Count for GEM Pad Muon System

SW 14 Aug 91

Assume 40-fold symmetry, strips 2 meters long and 5 mm wide
chambers 2 meters long by 9 degrees wide, active area

inner chambers:		4 layers/chamber
R=	4	
L=	6	
N chambers=	240	
N layers=	960	
chan/layer	126	
N chan	120576	

middle chambers:		4 layers/chamber
R=	6	
L=	10	
N chambers=	400	
N layers=	1600	
chan/chmbr	188	
N chan	301440	

outer chambers:		3 layers/chamber
R=	8	
L=	14	
N chambers=	560	
N layers=	1680	
chan/chmbr	251	
N chan	422016	

total chambers	1200
toal channels	844032

Channel Counting in the Muon Endcaps of GEM SW 13 Aug 91

strip occupancy= 5 Hz assuming 60KHz per unit eta. occfac = 0.105
max strip length= 2 meters

chambers at z= 6 rmax = 4

eta(i)	theta(i) rad	r(i)	theta(i) deg	strip length	5 mm inner width N strips/plane
2.500	0.164	0.992	9.386	0.110	1246
2.396	0.182	1.102	10.408	0.137	1385
2.281	0.204	1.239	11.672	0.176	1557
2.151	0.232	1.416	13.276	0.234	1779
2.003	0.268	1.650	15.374	0.326	2073
1.830	0.318	1.976	18.228	0.487	2483
1.623	0.390	2.463	22.321	0.814	3095
1.365	0.500	3.278	28.648	0.745	4119
1.190	0.591	4.023	33.844		
			total per plane		17737
			x 4 pl x 2 ends		141898

chambers at z= 10 rmax = 6

2.500	0.164	1.653	9.386	0.318	2077
2.327	0.195	1.971	11.149	0.464	2476
2.121	0.239	2.434	13.682	0.738	3059
1.866	0.307	3.172	17.599	1.354	3986
1.534	0.425	4.526	24.354	1.501	5688
1.280	0.542	6.027	31.078		
			total per plane		17286
			x 4 pl x 2 ends		138288

chambers at z= 14 rmax = 8

2.500	0.164	2.314	9.386	0.647	2908
2.258	0.208	2.961	11.943	1.115	3721
1.948	0.283	4.076	16.233	2.013	5122
1.570	0.410	6.089	23.507	1.966	7651
1.320	0.522	8.055	29.915		
			total per plane		19402
			x 3 pl x 2 ends		116412

total number of channels for 4-4-3 configuration 396598

Channel Counting in the Muon Endcaps of GEM SW 13 Aug 91

strip occupancy= 10 Hz assuming 60KHz per unit eta. occfac = 0.209
max strip length= 2 meters

chambers at z= 6 rmax = 4

eta(i)	theta(i) rad	r(i)	theta(i) deg	strip length	5 mm inner width N strips/plane
2.500	0.164	0.992	9.386	0.233	1246
2.292	0.201	1.225	11.539	0.369	1539
2.036	0.260	1.594	14.880	0.669	2003
1.702	0.361	2.263	20.668	1.760	2844
1.190	0.591	4.023	33.844		
			total per plane		7633
			x 4 pl x 2 ends		61061

chambers at z= 10 rmax = 6

2.500	0.164	1.653	9.386	0.700	2077
2.154	0.231	2.352	13.239	1.588	2956
1.661	0.375	3.940	21.507	2.016	4952
1.290	0.537	5.957	30.784		
			total per plane		9985
			x 4 pl x 2 ends		79877

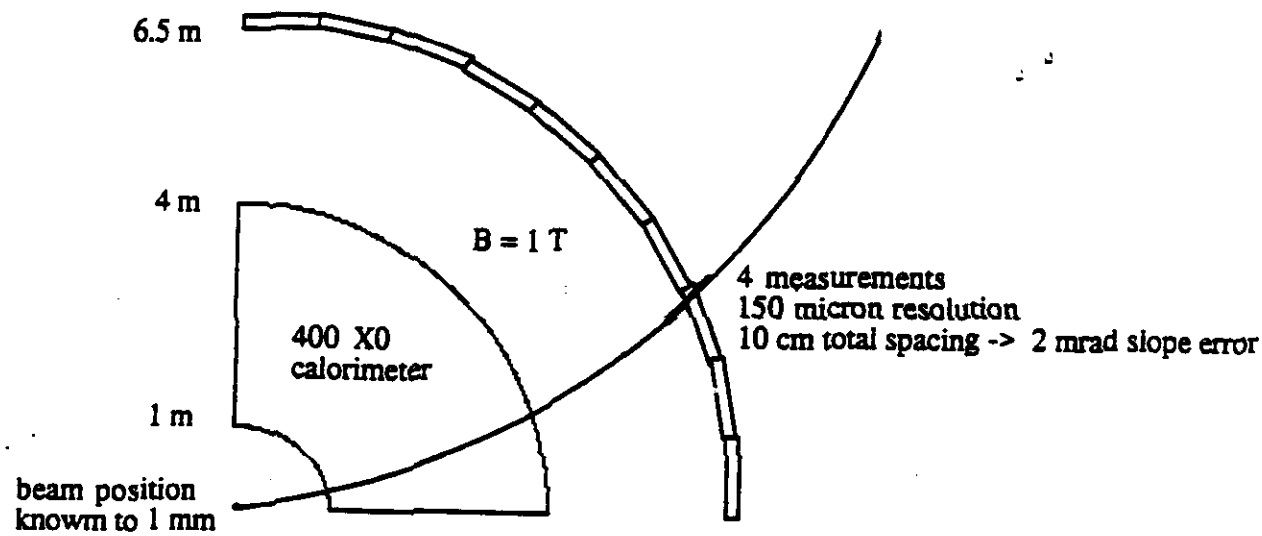
chambers at z= 14 rmax = 8

2.500	0.164	2.314	9.386	1.485	2908
2.015	0.265	3.799	15.183	1.968	4774
1.620	0.391	5.767	22.390	2.195	7247
1.330	0.517	7.962	29.631		
			total per plane		14929
			x 3 pl x 2 ends		89573

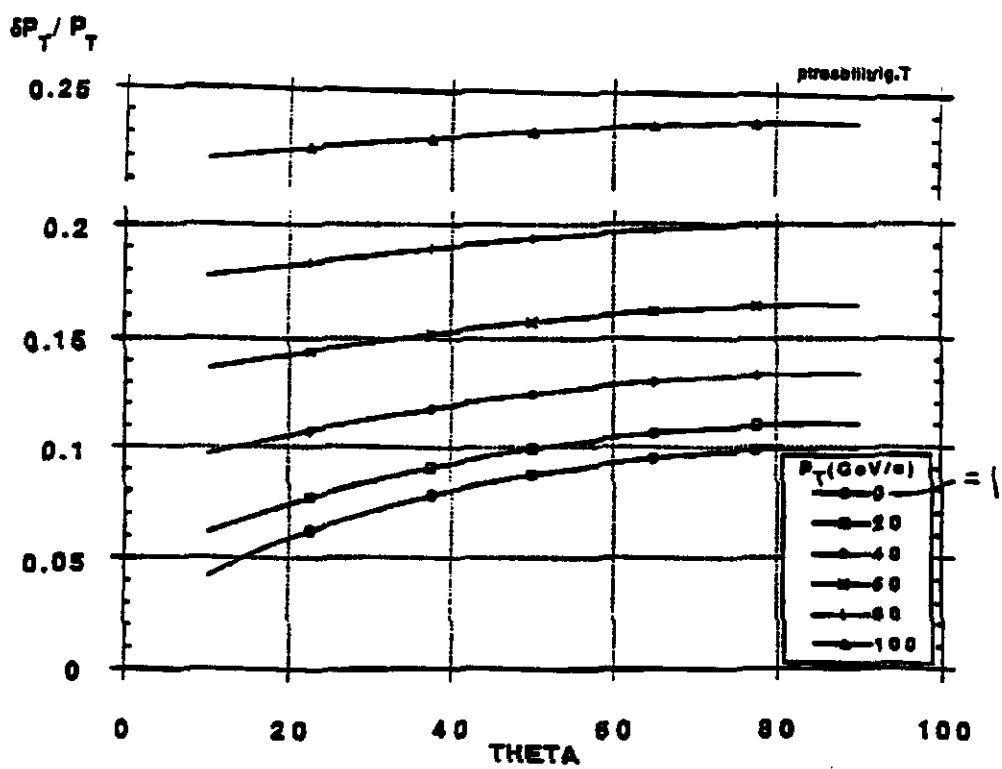
total number of channels for 4-4-3 configuration 230512

TRIGGERING using the Middle Superlayer

Basic idea: measure a vector in the middle superlayer } point-line
assume the beam position } momentum measurement

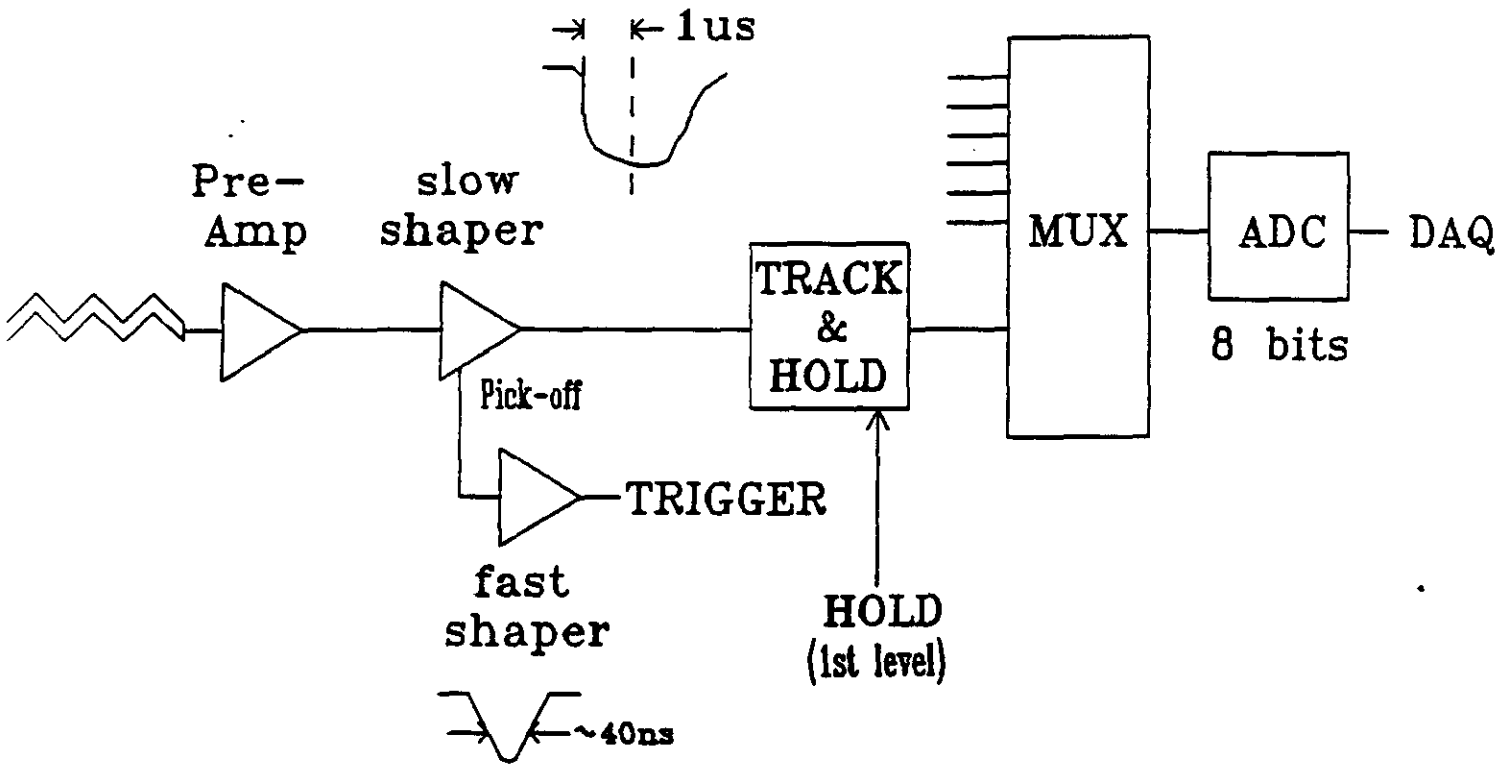


Resolution calculation -- Larry Rosenson



READOUT

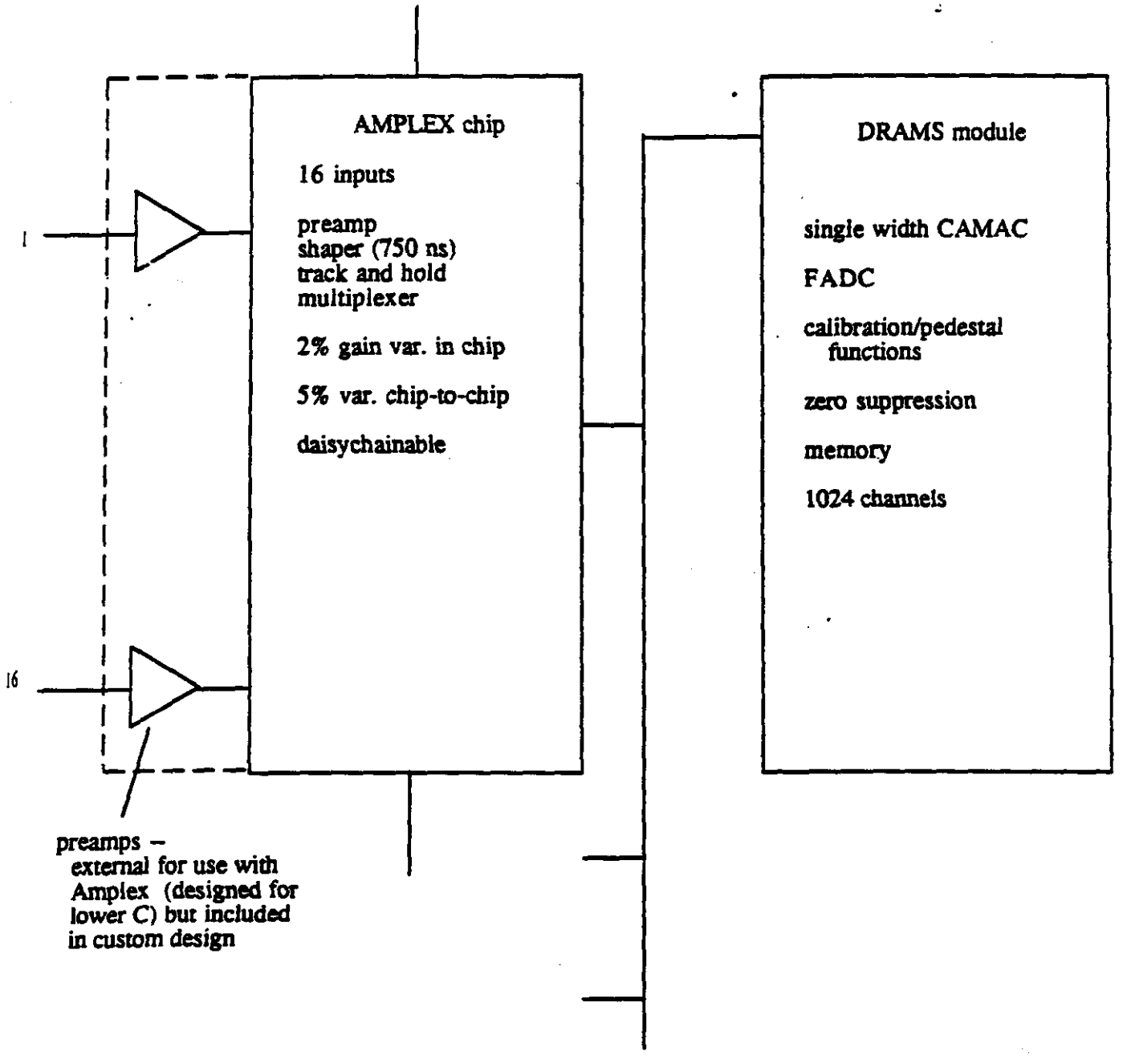
Long integration time (~1us)
⇒ built-in 1st level trigger delay
No analog pipe lines



- Same detector for trigger
- Can be done with existing technology
- Path for precision charge measurement does not require 60 MHz clock

EXAMPLE OF READOUT WITH CURRENT TECHNOLOGY

- Existing devices have nearly the right parameters
- circuits for chamber tests can be prepared for next summer...



SHORT-TERM R & D GOALS

- Construct several large pad chambers ~ 1 m x 2 m
- Develop and implement readout chain based on Amplex + DRAMS
- Test chambers in a beam -- next summer
  - -> Measure resolution
  - -> Study effects of angle of incidence
  - -> Study systematics
- Gas studies
  - -> drift velocities
  - -> Lorentz angles
- Develop point-line triggering scheme
  - -> Algorithm
  - -> Implementation

Talk by Bing Zhou on

Pressurized Drift Tube Option

High Precision Cylindrical Drift Tube Technology

Bing Zhou
Physics Dept., Boston University
Aug., 1991

1 General Description

Cylindrical drift tube is a very simple tracking device, and has been used for high precision tracking in magnetic field by many experiments. The technology is well understood and established. Its basic working principle has been well documented by F. Sauli(see appendix).

We propose to use pressurized stainless steel drift tubes for GEM muon tracking system is based on the following considerations:

(1) Good resolution: single wire resolution $\sim$ 150 microns;

(2) Most robust muon system in large scale;

(3) Close to 100% acceptance in ϕ;

(4) Well understood performance in magnetic field;

(5) Easily pressurize to improve the resolution;

(6) Modular construction–easy for alignment and transportation;

(7) Low cost.

As useful information we list basic operation formula of the drift tubes in a magnetic field below:

- Electric field inside tube: $E(r) = HV_{wire}/r/ln(b/a)$, where a is wire diameter and b is tube diameter.

- Drift velocity (B-field =0) $V_0 = k(eE/m)\tau \sim f(E, k, \tau)$, where k is a gas dependent constant, τ is mean time of collision between drift electrons and the gas molecules, and m is electron mass.

- In the magnetic field drift velocity (three components) will depend on the B-field also: $V_r = V_0 \times (1 + (\omega_r\tau)^2)/(1 + (\omega\tau)^2)$ $V_T = V_0 \times (\omega_z\tau + \omega_r\omega_T\tau^2)/(1 + (\omega\tau)^2)$ $V_z = V_0 \times (\omega_T\tau + \omega_r\omega_z\tau^2)/(1 + (\omega\tau)^2)$ where, $\omega_c(\omega_r, \omega_T, \omega_z) = eB/mc = e/mc \times (B_r, B_T, B_z)$ and $tan\theta_{Lorentz} = \omega\tau$.

- The drift time and drift distance relationship is: $T(r) = \int_a^r dr'/V_r(r')$

In order to operate the drift tube style chamber in B-filed to measure muon momentum, based on above formula, we need to know the following parameters:

(1) Accurate magnetic field map and wire high voltage;

(2) Drift velocity vs. electric field for operating drift gas;

(3) Lorentz angle vs. E-field and B-field for operating drift gas.

LIST OF COLLABORATORS

for the S.S. Pressurized Drift Tubes muon system

1 **BOSTON UNIVERSITY**

S. Ahlen, T. Johnson, D. Loomba, A. Marin, D. Osborne, J. Shank, D. Warner, S. Whitaker, B. Wilson, B. Zhou

2 **BROWN UNIVERSITY**

M. Wigdoff

3 **INDIANA UNIVERSITY**

D. Alyea, C. Bower, R. Heinz, J. Musser, J. Pitts

4 **INSTITUTE FOR ATOMIC PHYSICS, BUCHAREST**

A. Aculai, C. Blaj, H. Bozdoc, L. Butacu, M. Ciobanu, D. Ighicianu, D. Lazarovici, S. Miron, G. Pascovici, M. Pentia, D. Pop, V. Popa, G. Radulescu, D. Spanu, V. Valeanu

5 **INSTITUTE OF HIGH ENERGY PHYSICS, BEIJING**

W. Gu, Y. Gu, Y. Guo, Y. Huang, J. Li, C. Mao, H. Sheng, R. Xu, D. Zhang, B. Zhuang

6 **JOINT INSTITUTE FOR NUCLEAR RESEARCH, DUBNA**

G. Alekseev and others

7 **LOS ALAMOS NATIONAL LABORATORY**

R. Barber, M. Brooks, T. Coan, J. Hanlon, D. Lee, G. Sanders, B. Smith

8 **MIT**

I. Pless and others

9 **WASHINGTON UNIVERSITY**

J. Beatty, D. Ficenec

Other groups welcome !

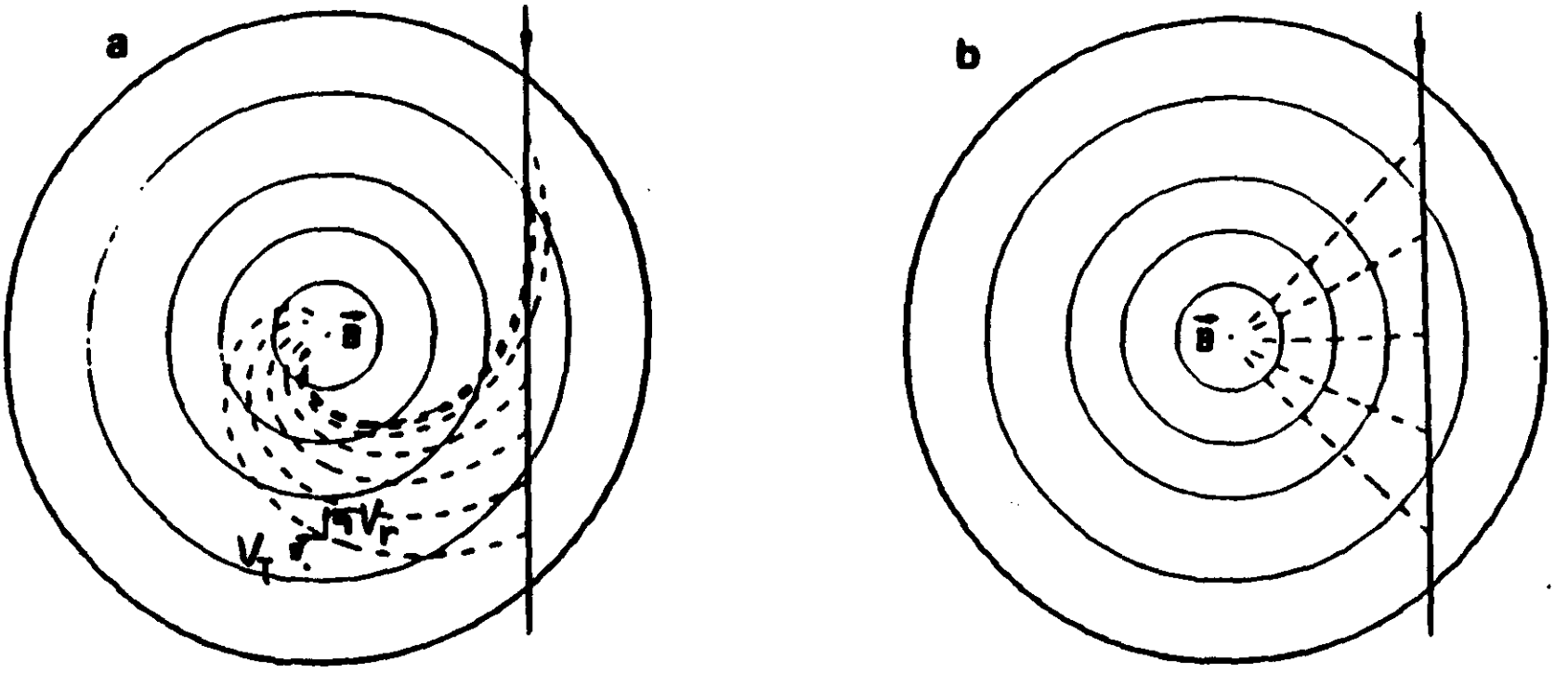


Fig. 8. Electron drift trajectories (dashed lines) in a 1 in. diameter drift tube at 15 kG B-field. The solid line with the arrow is the particle track and the thin solid circles inside the tube represent the E-field potentials. (a) for 50–50 argon–ethane gas, (b) for DME gas.

Basic Performance of drift tube in B-field:

Dirft velocity and Lorentz angle :

$$E_{field} = HV_{wire}/r/Ln(b/a)$$
$$V_0 = k(eE/m)\tau \sim f(E, k, \tau)$$

$$V_r = V_0 \times (1 + (\omega_r\tau)^2)/(1 + (\omega\tau)^2)$$
$$V_T = V_0 \times (\omega_z\tau + \omega_r\omega_T\tau^2)/(1 + (\omega\tau)^2)$$
$$V_z = V_0 \times (\omega_T\tau + \omega_r\omega_z\tau^2)/(1 + (\omega\tau)^2)$$

$$\vec{\omega}_c(\omega_r, \omega_T, \omega_z) = e\vec{B}/mc = e/mc \times (B_r, B_T, B_z)$$
$$tan\theta_{Lorentz} = \omega\tau$$

Time-Space : $\text{Drifttime(r)} = \int_a^r dr'/V_r(r')$

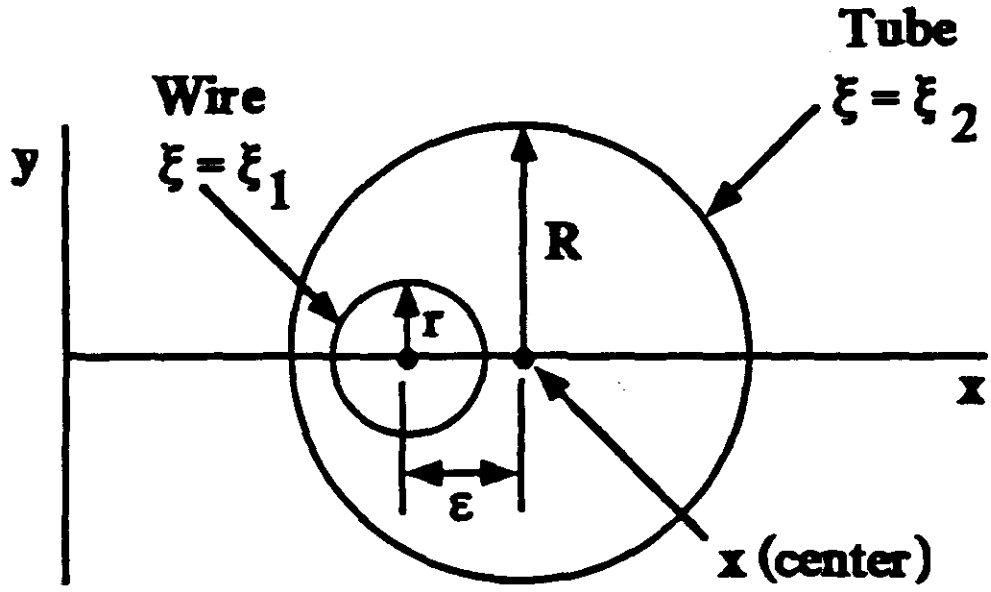
Experimental data needed for space-time function:

1) Accurate magnetic field map and wire high voltage;

2) Drift velocity vs. electric field for used drift gas;

3) Lorentz angle vs. E-field and B-field for used drift gas.

ELECTRIC FIELD IN DRIFT TUBE CAN BE EASILY CALCULATED PRECISELY



BIPOLAR COORDINATES

$$x = a \sinh(\xi) / (\cosh(\xi) + \cos(\theta))$$

$$y = a \sin(\theta) / (\cosh(\xi) + \cos(\theta))$$

$$\varepsilon = (R^2 + a^2)^{1/2} - (r^2 + a^2)^{1/2}$$

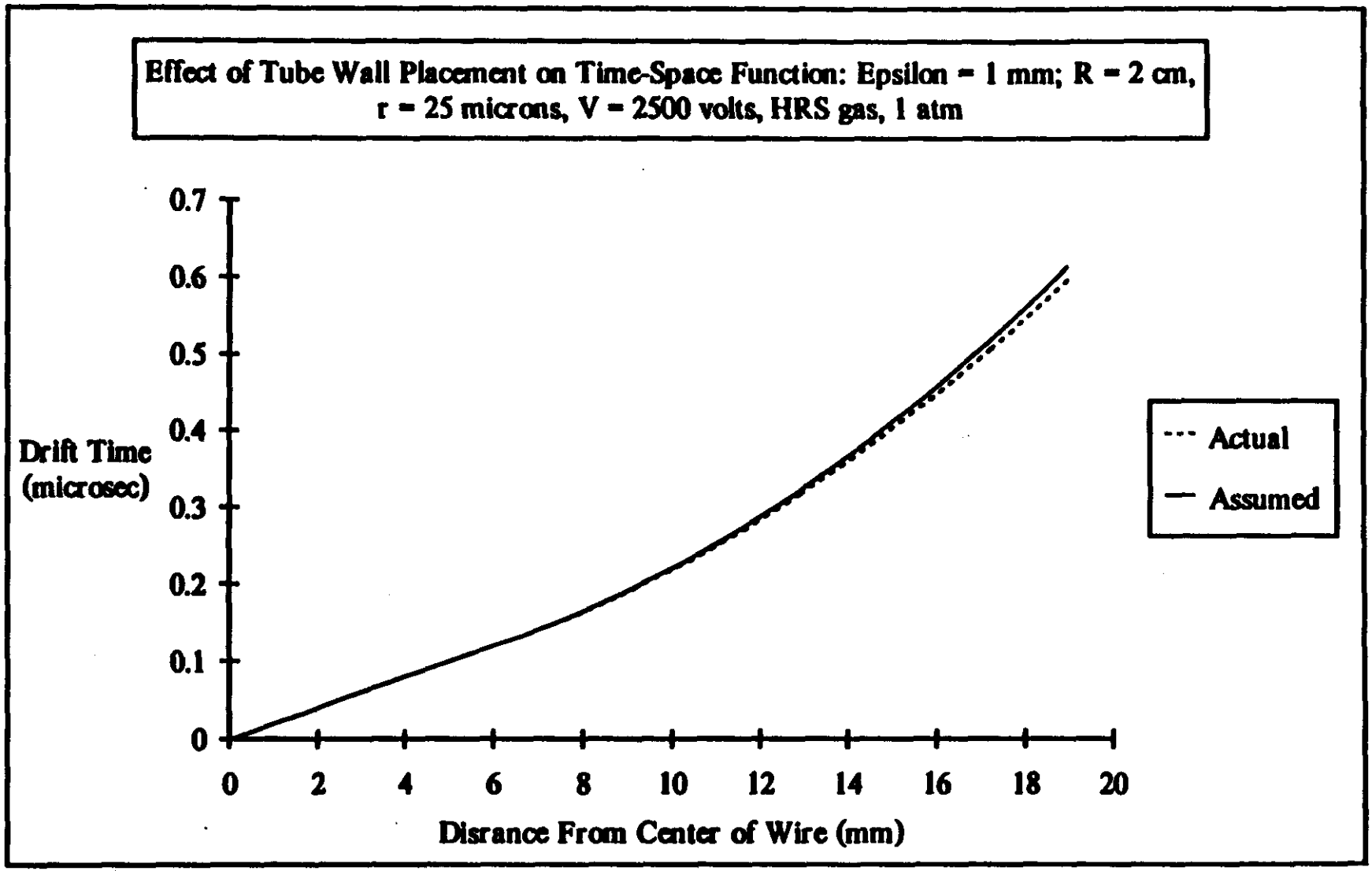
$$x\,(\text{center}) = a \coth(\xi_1)$$

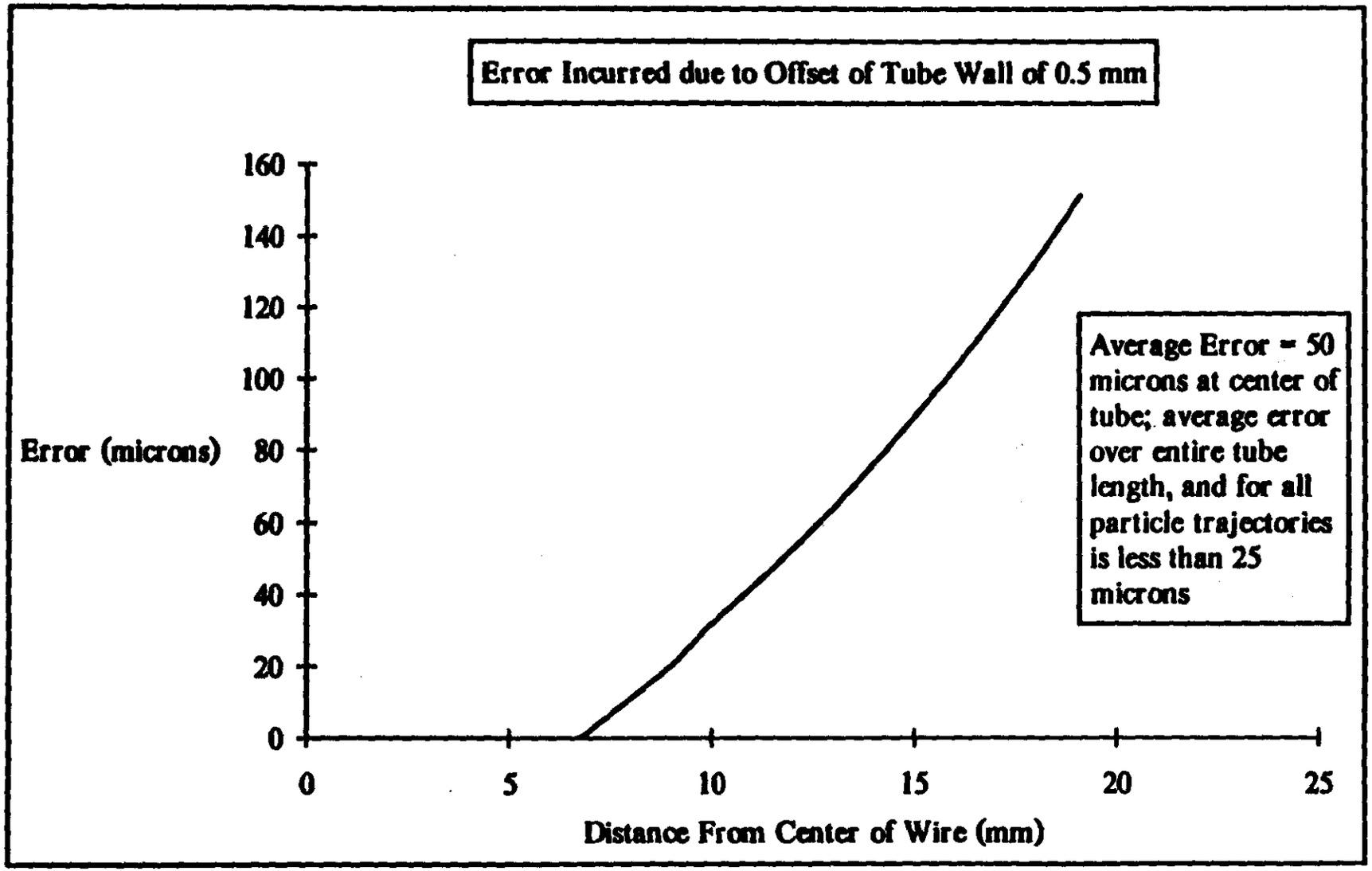
$$r = a / \sinh(\xi_1)$$

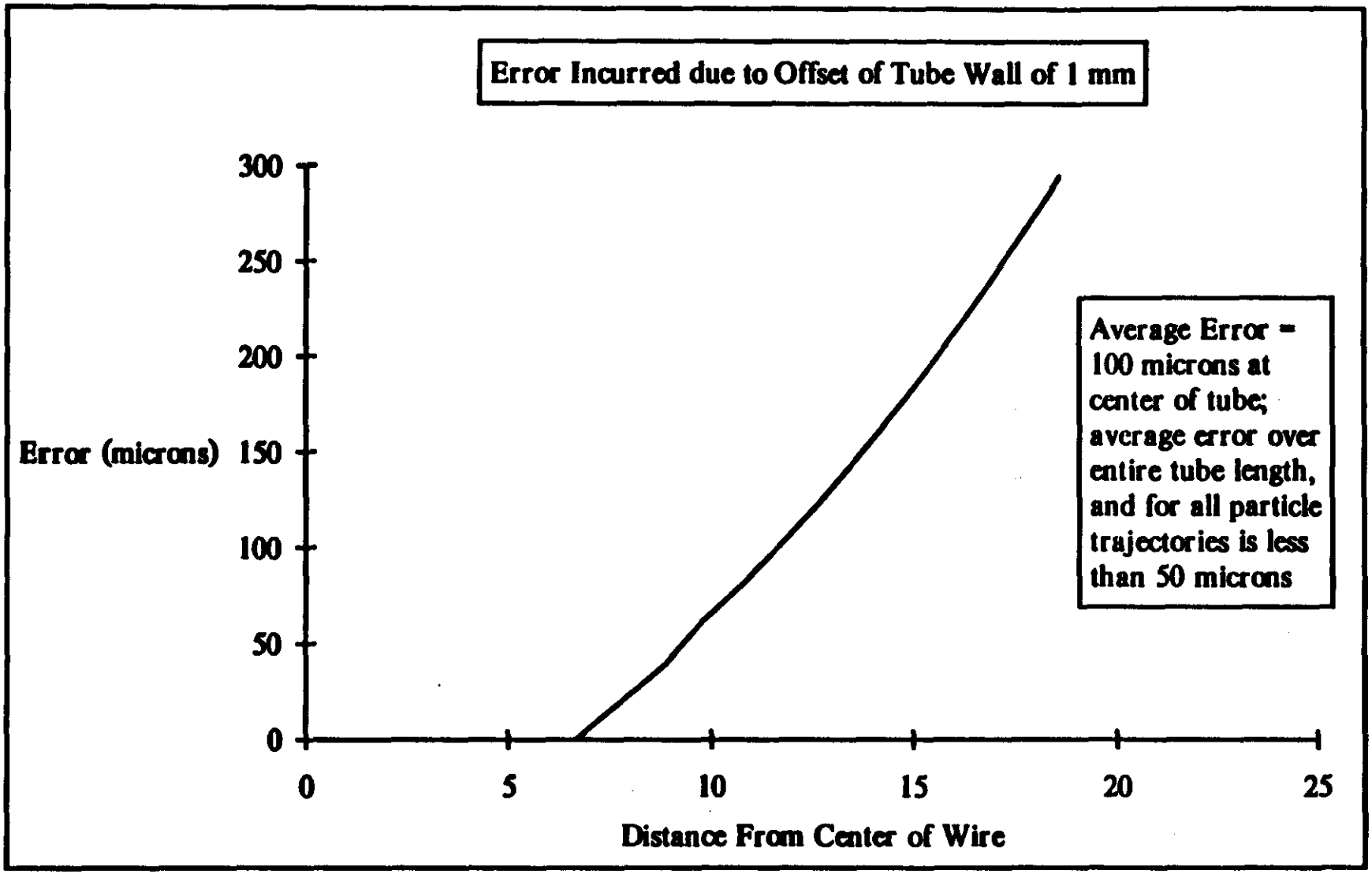
$$R = a / \sinh(\xi_2)$$

$$E_x = -V(\cos(\theta)\cosh(\xi) + 1) / [a(\xi_1 - \xi_2)]$$

$$E_y = V(\sin(\theta)\sinh(\xi)) / [a(\xi_1 - \xi_2)]$$


Effect of Tube Wall Placement on Time-Space Function: Epsilon = 1 mm; R = 2 cm, r = 25 microns, V = 2500 volts, HRS gas, 1 atm
Drift Time (microsec)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
2
4
6
8
10
12
14
16
18
20
Disrance From Center of Wire (mm)
Actual
Assumed


Error Incurred due to Offset of Tube Wall of 0.5 mm
Error (microns)
160
140
120
100
80
60
40
20
0
0
5
10
15
20
25
Distance From Center of Wire (mm)
Average Error = 50 microns at center of tube; average error over entire tube length, and for all particle trajectories is less than 25 microns


Error Incurred due to Offset of Tube Wall of 1 mm
Error (microns)
300
250
200
150
100
50
0
0
5
10
15
20
25
Distance From Center of Wire
Average Error = 100 microns at center of tube; average error over entire tube length, and for all particle trajectories is less than 50 microns

Stainless steel drift tube operation record

xperiment	HRS	CDF	EXAM
	PEP (1982-86) e^+e^-	Tevatron (1988-now) $p\bar{p}$	Balloon (1988) cosmic rays
lumber of layers	10	3	8
lumber of tubes	1792*3	2016	600
ube length	3.7 m	3.0 m	3.7 m
iameter	2.54 cm	2.54 cm	3.8 cm
Vall thickness	152 μm	200 μm	152 μm
veraged X_0 /tube	2.9%	3.3%	2.9%
as	$Ar:CO_2:CH_4$ (89:90:1)		Ar:ethane (50:50)
perating mode	limited streamer	limited streamer	proportional
ax. drift time	300 ns		500 ns
esolution/wire	200μm	200μm	170μm
Iagnetic field	1.6 T	1.5 T	0
ever arm	1.7 m	1.3 m	-
p/p	0.1%/GeV	0.2%/GeV	-
-φ	drift time	drift time	drift time
	-	charge division	drift time
ccupancy		5%	

Ref.:

HRS D. Rubin et. al., NIM A203(1982)119.
G. Baranko, Ph.D thesis at Indiana Univ. (1985).

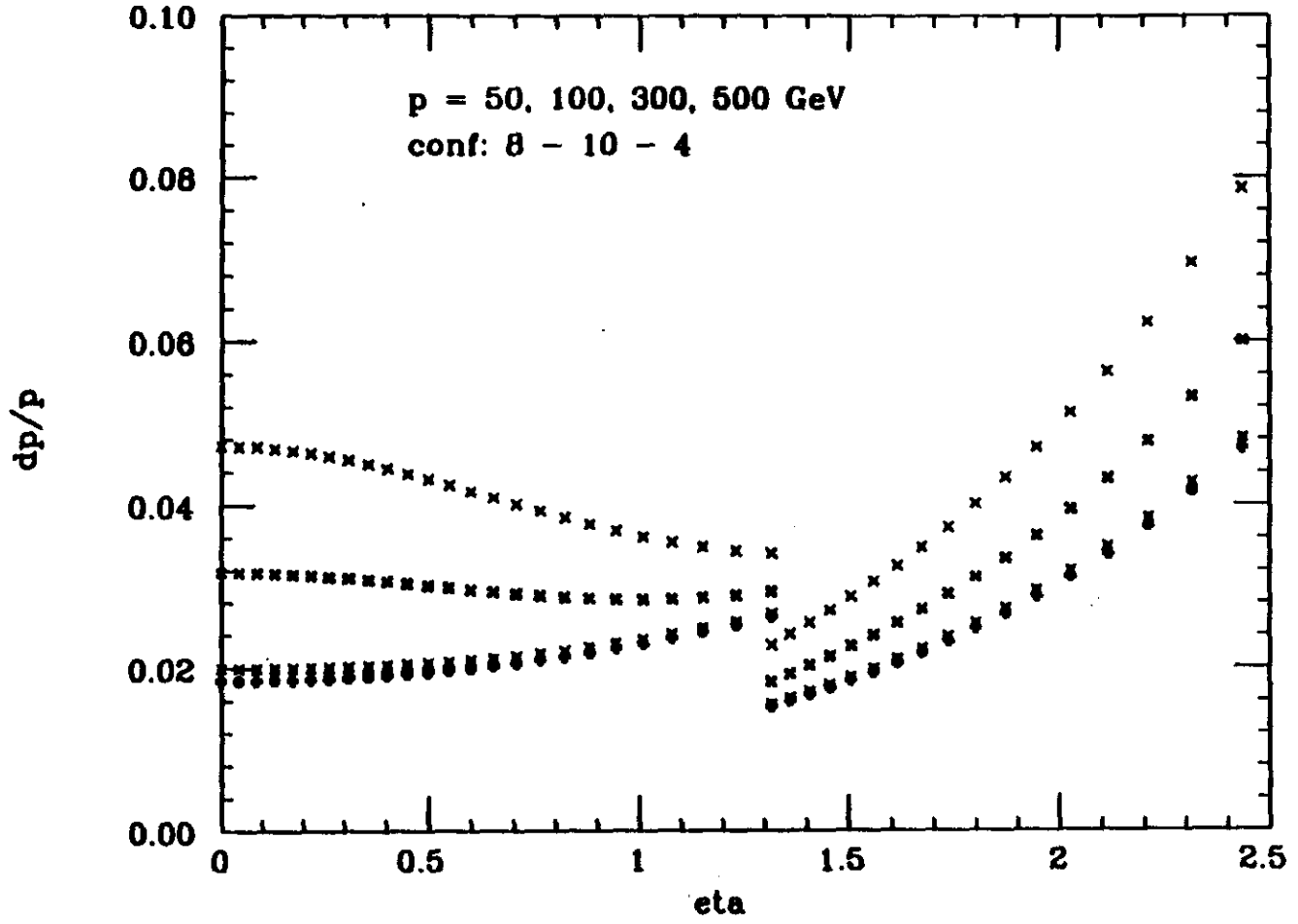
CDF S. Bhadra et. al., NIM A268(1988)92.
S. Bhadra et. al., NIM A269(1988)33.

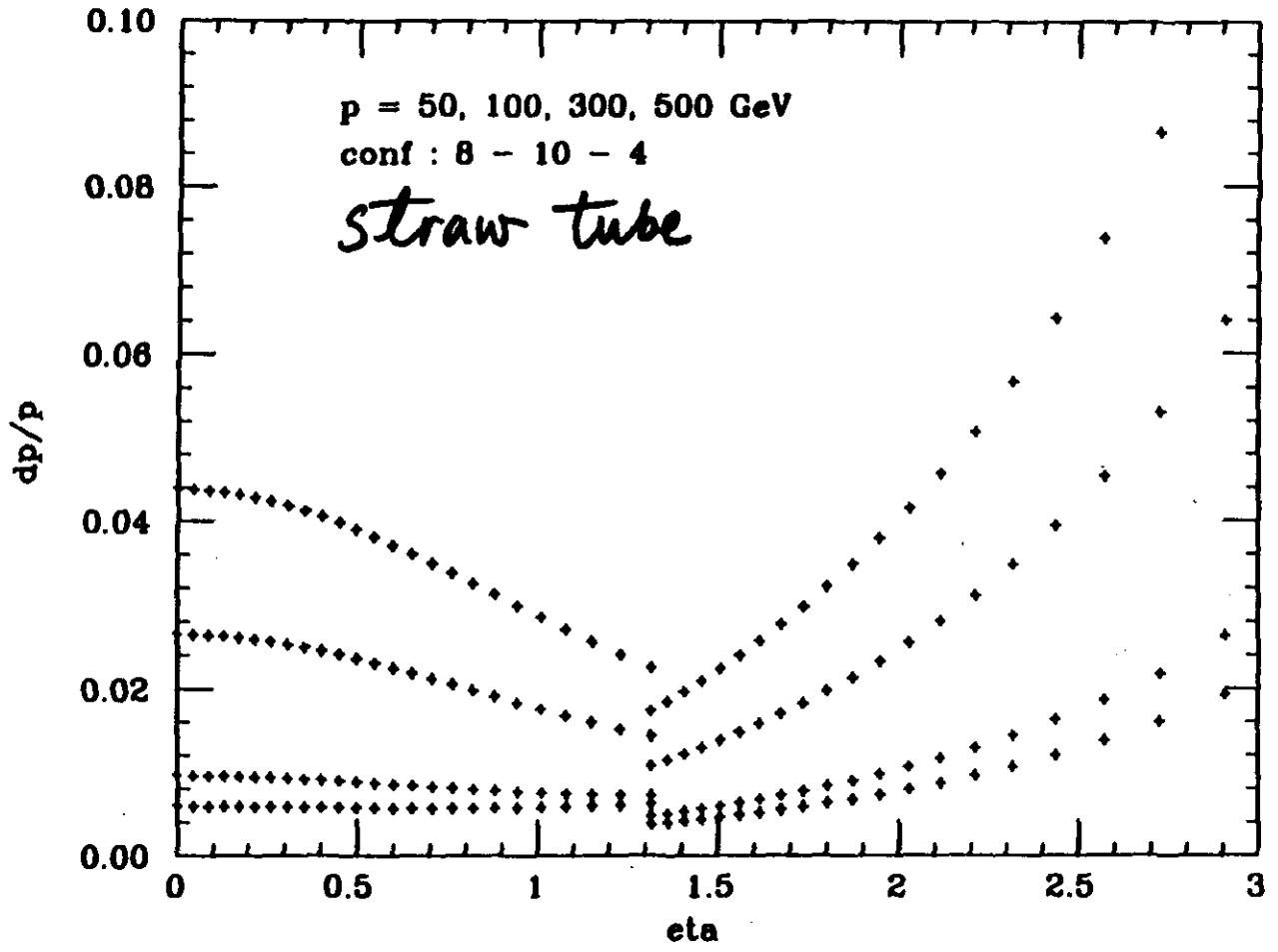
EXAM A. Tomasch et. al., NIM (1985).
T. Coan, Ph.D thesis at UC Berkeley (1989).

Z
X
Y

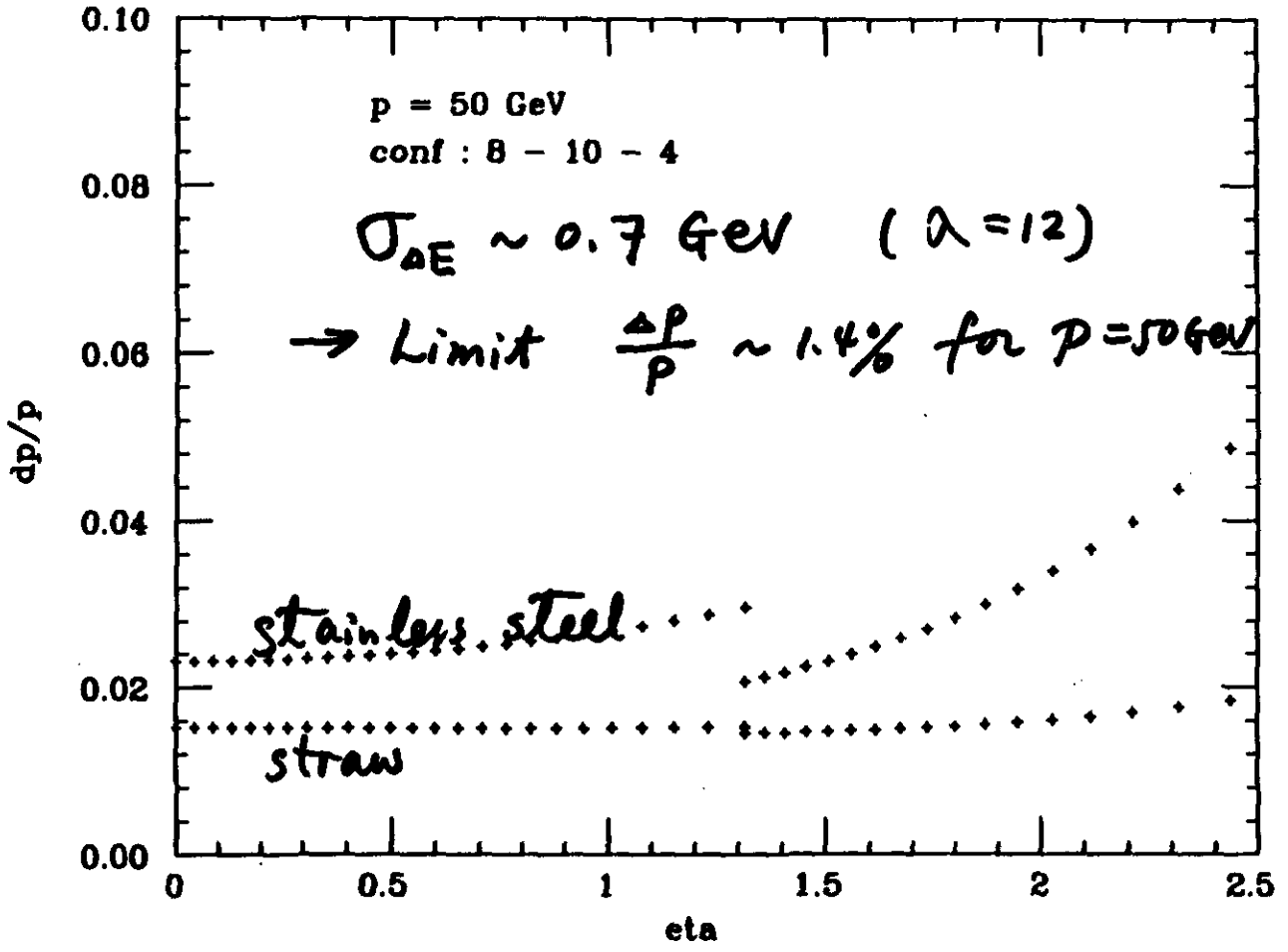
Concern about stainless steel tube

$\Delta p/p \sim 2\%$ (Limit)

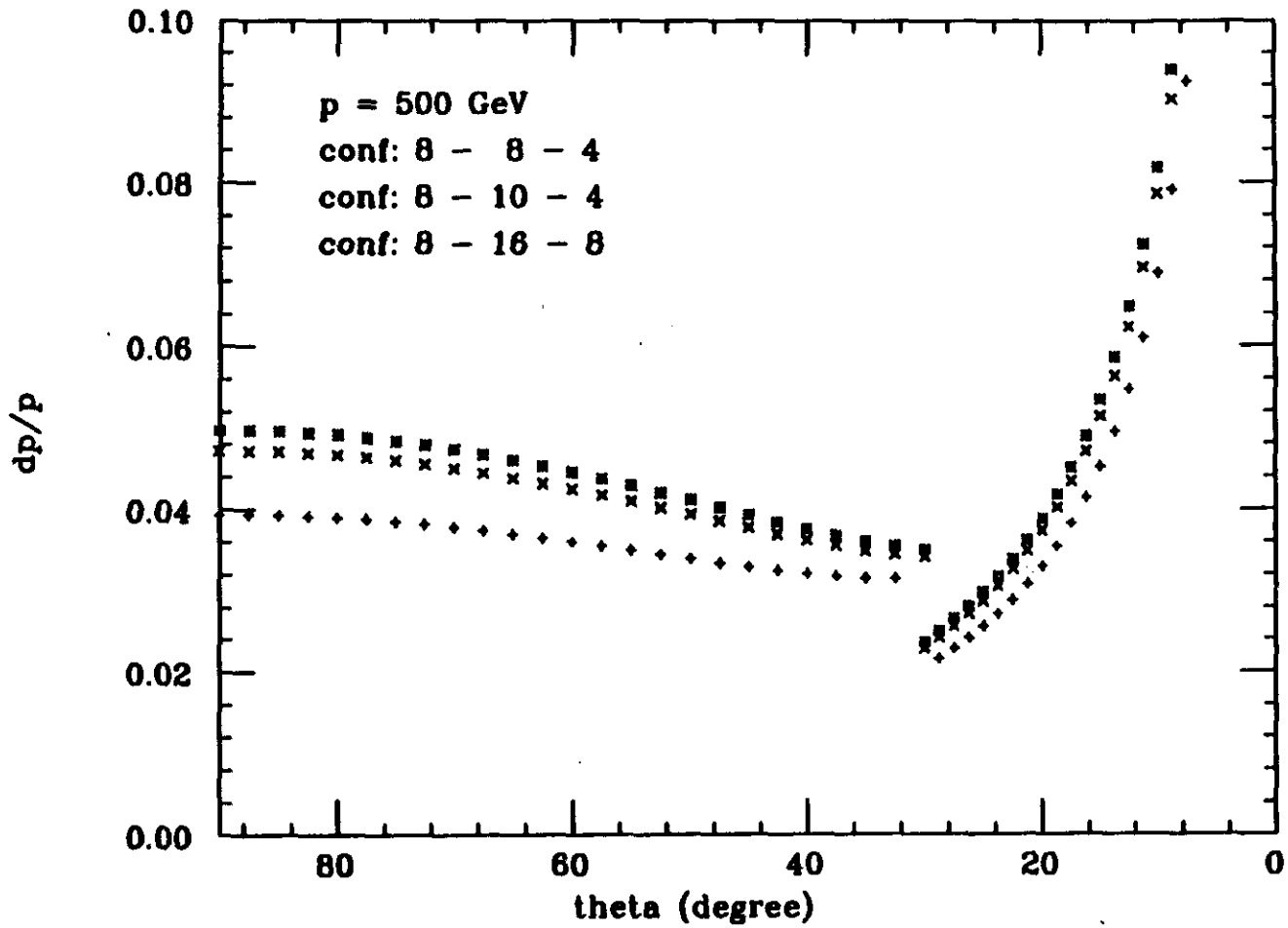



p = 50, 100, 300, 500 GeV
conf : 8 - 10 - 4
straw tube
dp/p
eta
0.10
0.08
0.06
0.04
0.02
0.00
0
0.5
1
1.5
2
2.5
3

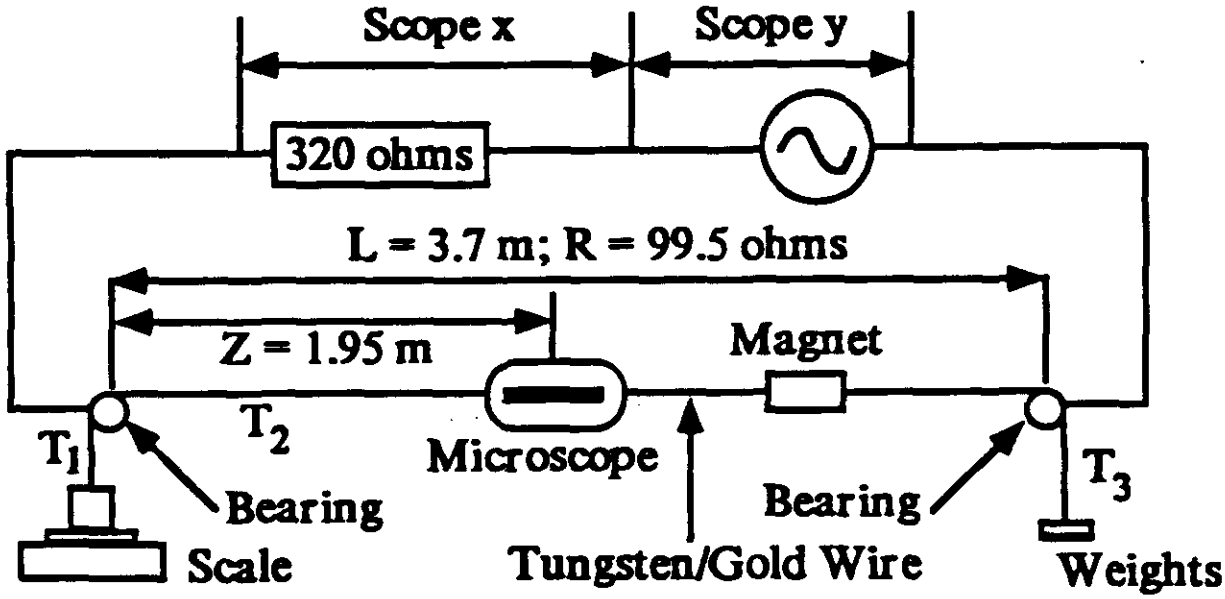
$$P_\mu = \Delta E + P_{chamber}$$

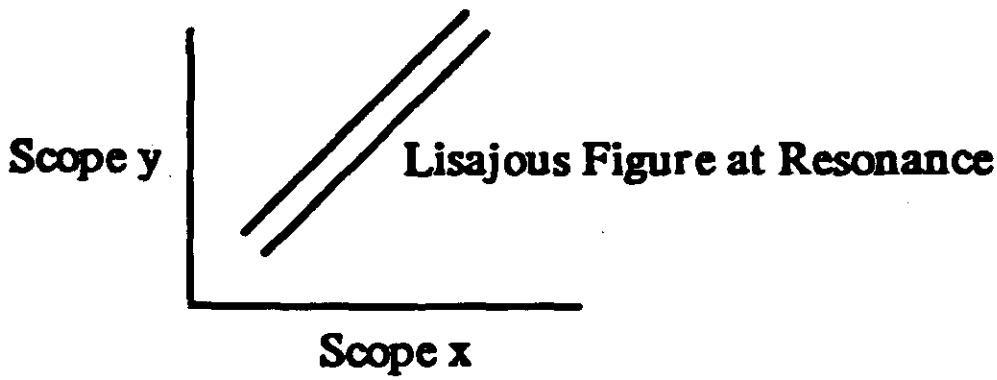


Configuration



Wire Tests





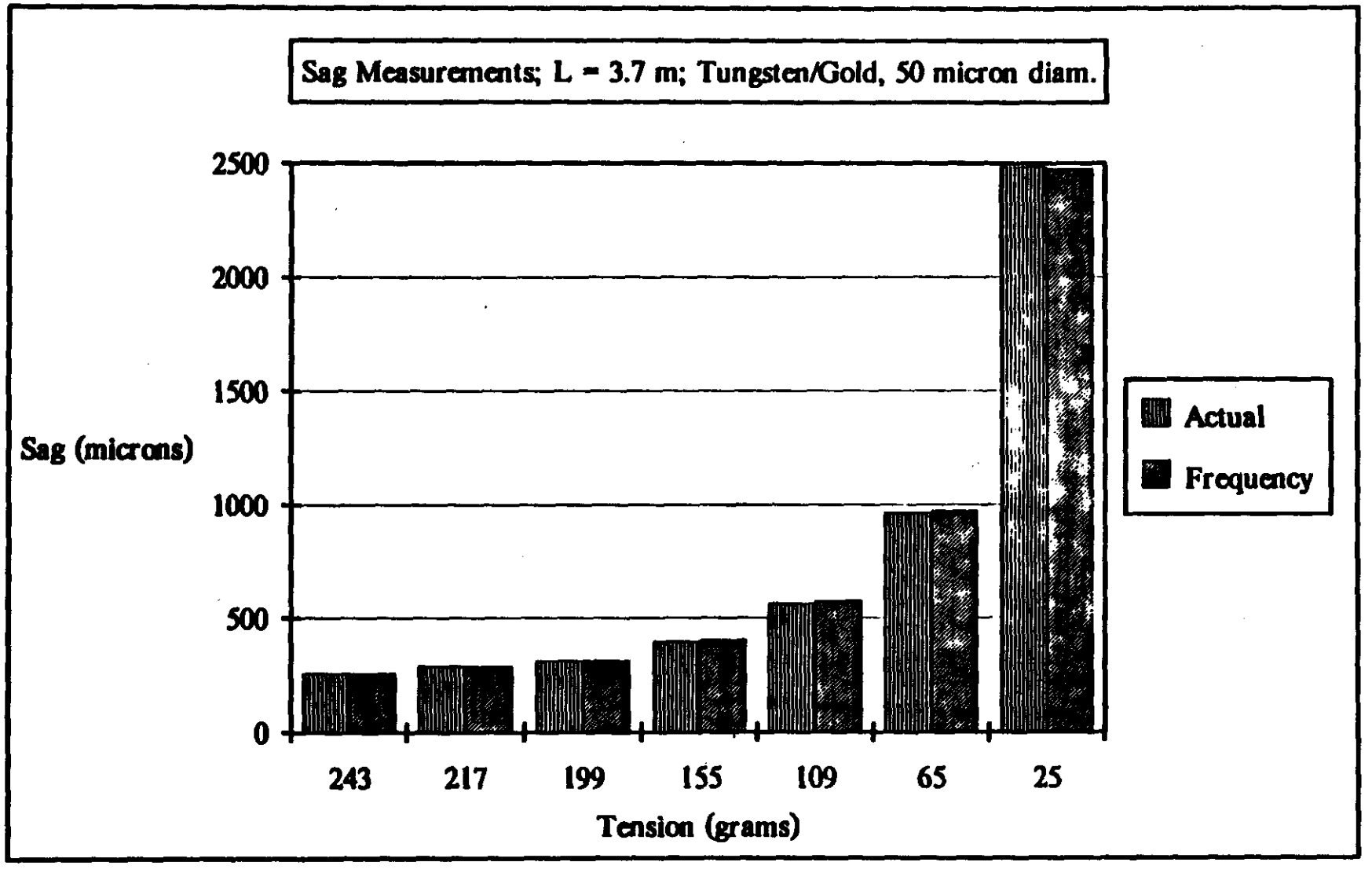
R = 99.5 ohms implies diameter = 2r = 49.6 microns (70 F)

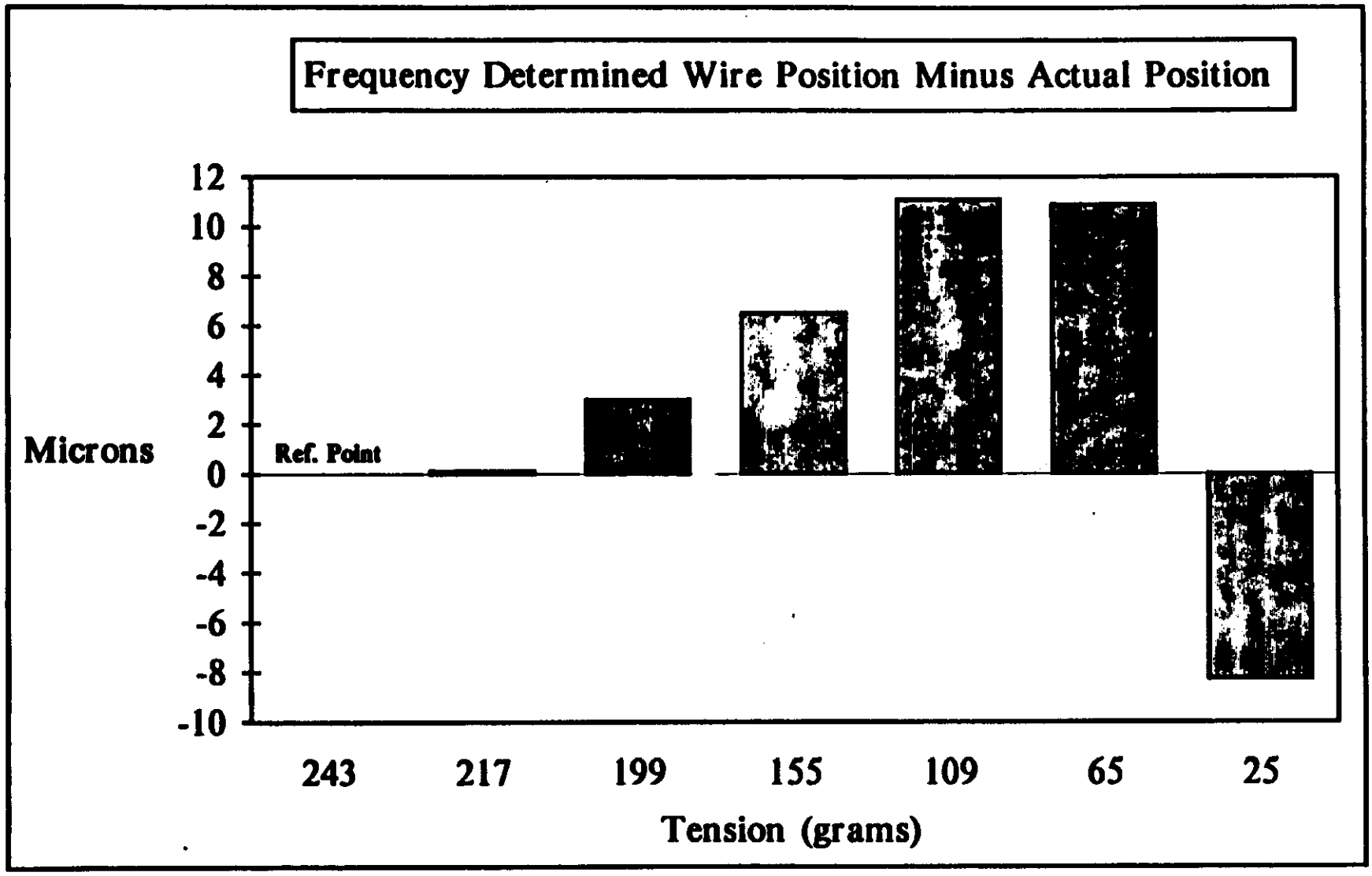
S = wire sag
ρ = mass density = 19.3 g/cc (gold and tungsten)
g = gravitational acceleration
f = fundamental resonant frequency
T = tension in wire

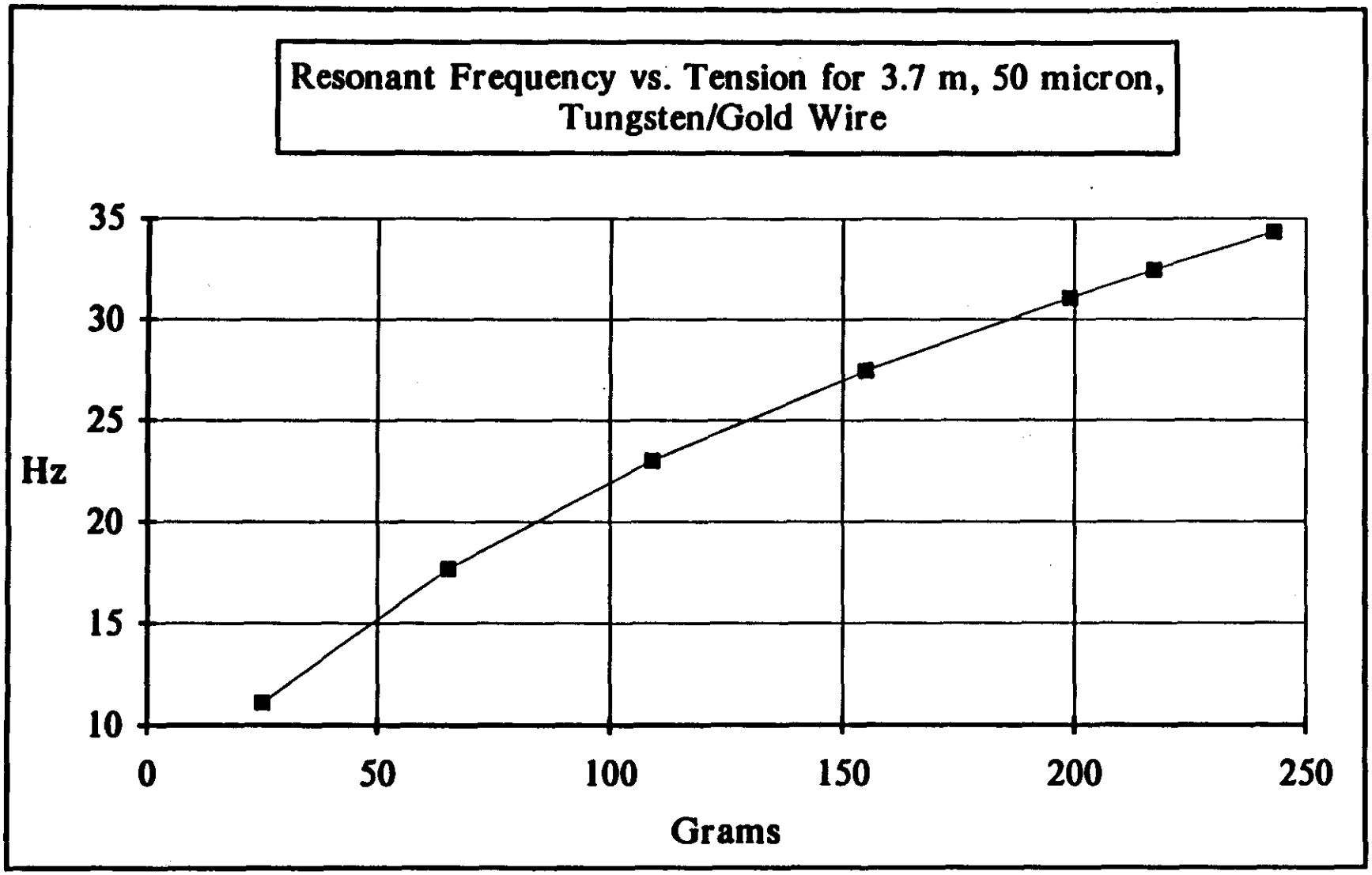
$$T = \rho\pi r^2(2Lf)^2$$

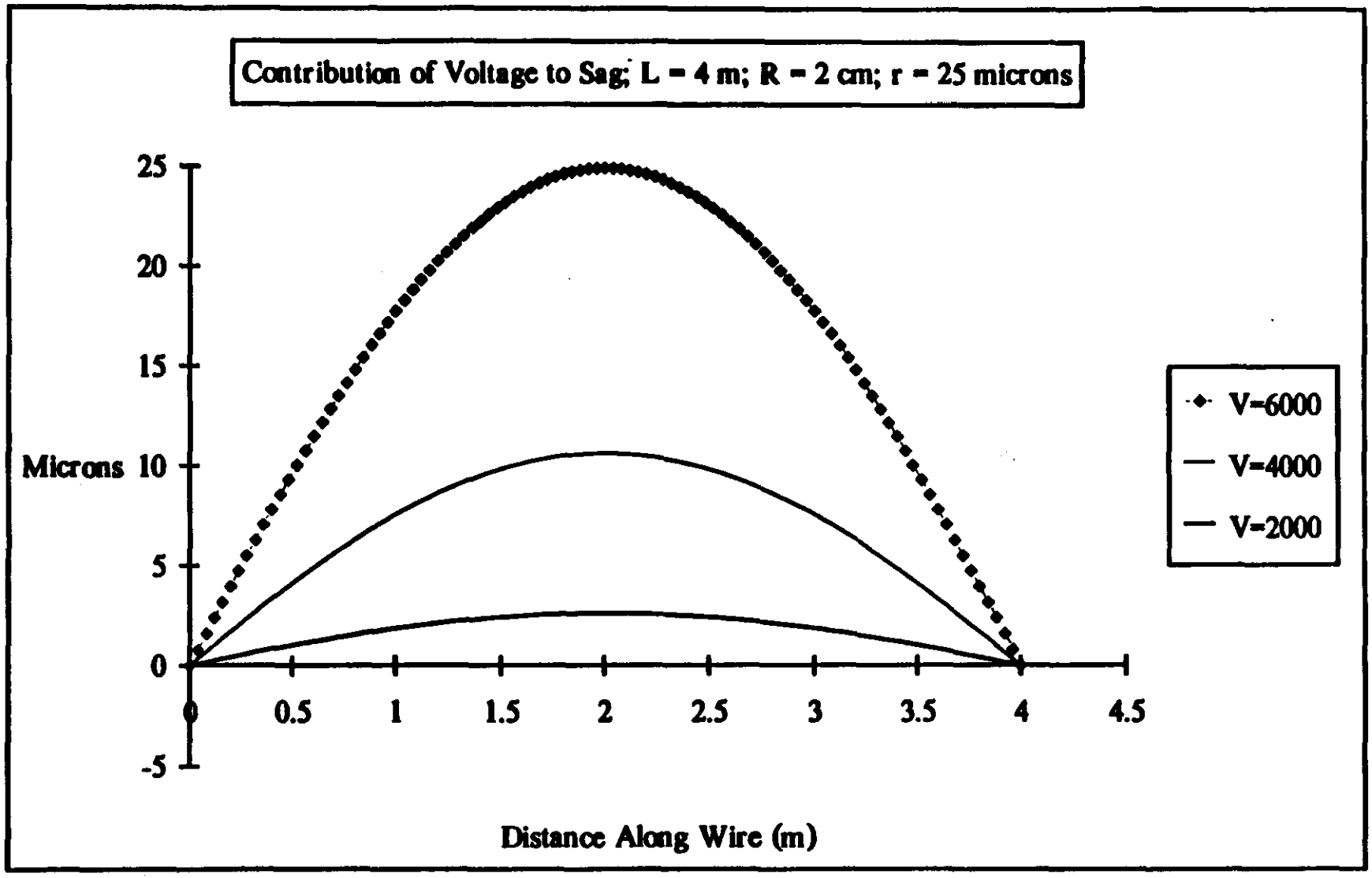
$$\boxed{S = \rho\pi r^2 g(Z^2 - LZ)/(2T) = g((Z/L)^2 - (Z/L))/(8f^2)}$$

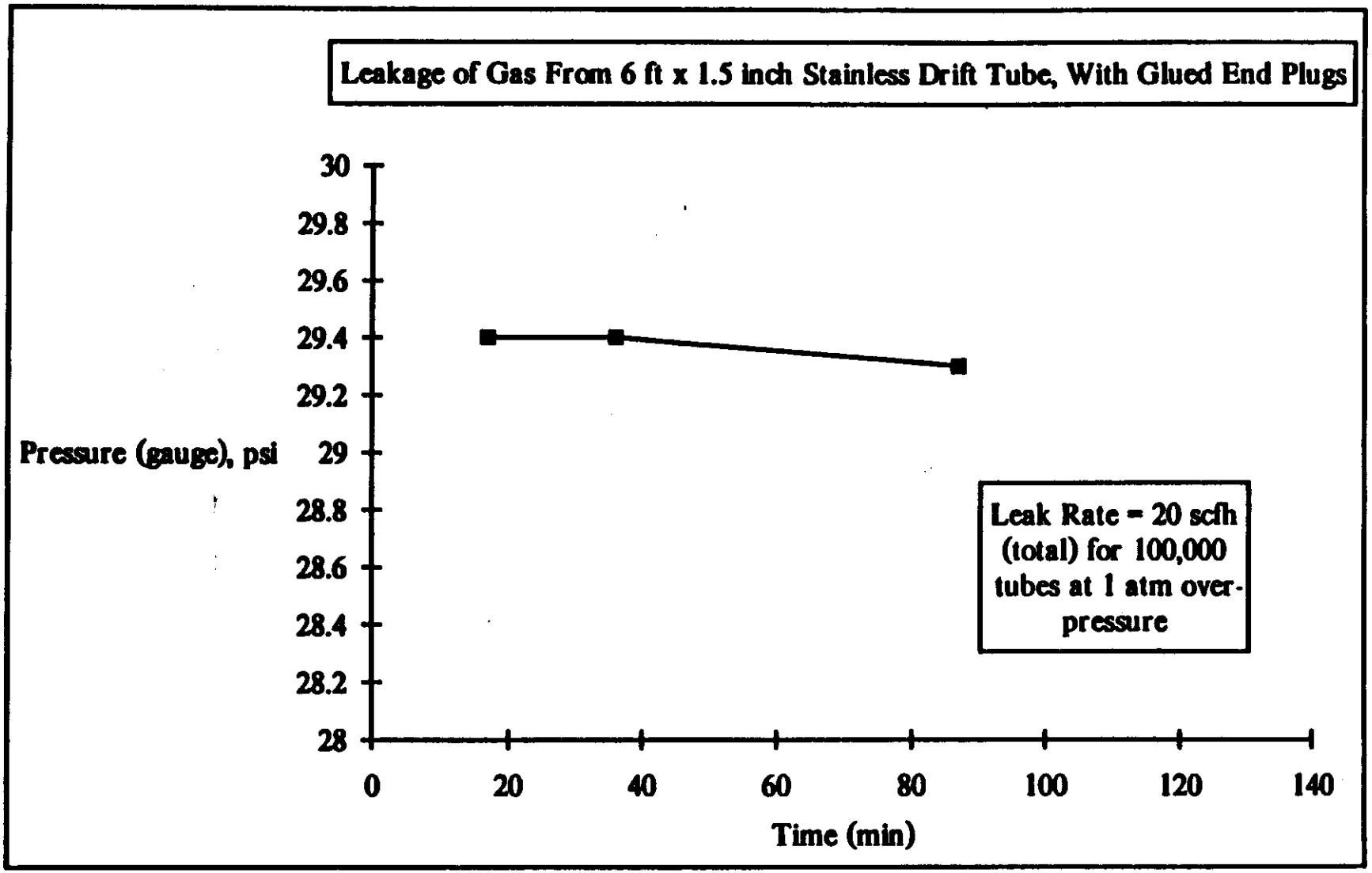
NOTE: S depends on f only, and has no additional dependence on T or r

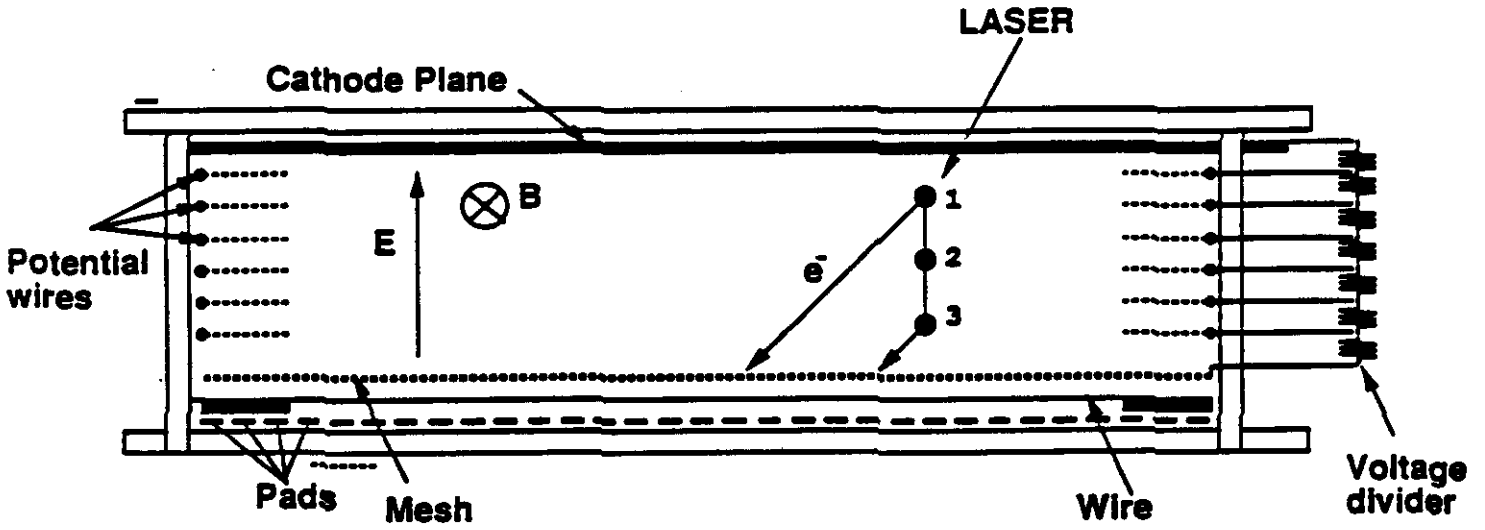

Sag Measurements; L = 3.7 m; Tungsten/Gold, 50 micron diam.
Sag (microns)
2500
2000
1500
1000
500
0
243
217
199
155
109
65
25
Tension (grams)
Actual
Frequency


Frequency Determined Wire Position Minus Actual Position
Microns
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
Ref. Point
243
217
199
155
109
65
25
Tension (grams)


Resonant Frequency vs. Tension for 3.7 m, 50 micron, Tungsten/Gold Wire
35
30
25
20
15
10
Hz
0
50
100
150
200
250
Grams


Contribution of Voltage to Sag; L = 4 m; R = 2 cm; r = 25 microns
Microns
25
20
15
10
5
0
-5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Distance Along Wire (m)
V=6000
V=4000
V=2000


Leakage of Gas From 6 ft x 1.5 inch Stainless Drift Tube, With Glued End Plugs
Pressure (gauge), psi
30
29.8
29.6
29.4
29.2
29
28.8
28.6
28.4
28.2
28
0
20
40
60
80
100
120
140
Time (min)
Leak Rate = 20 scfh (total) for 100,000 tubes at 1 atm over-pressure


LASER
Cathode Plane
B
E
1
2
3
e-
Potential wires
Pads
Mesh
Wire
Voltage divider

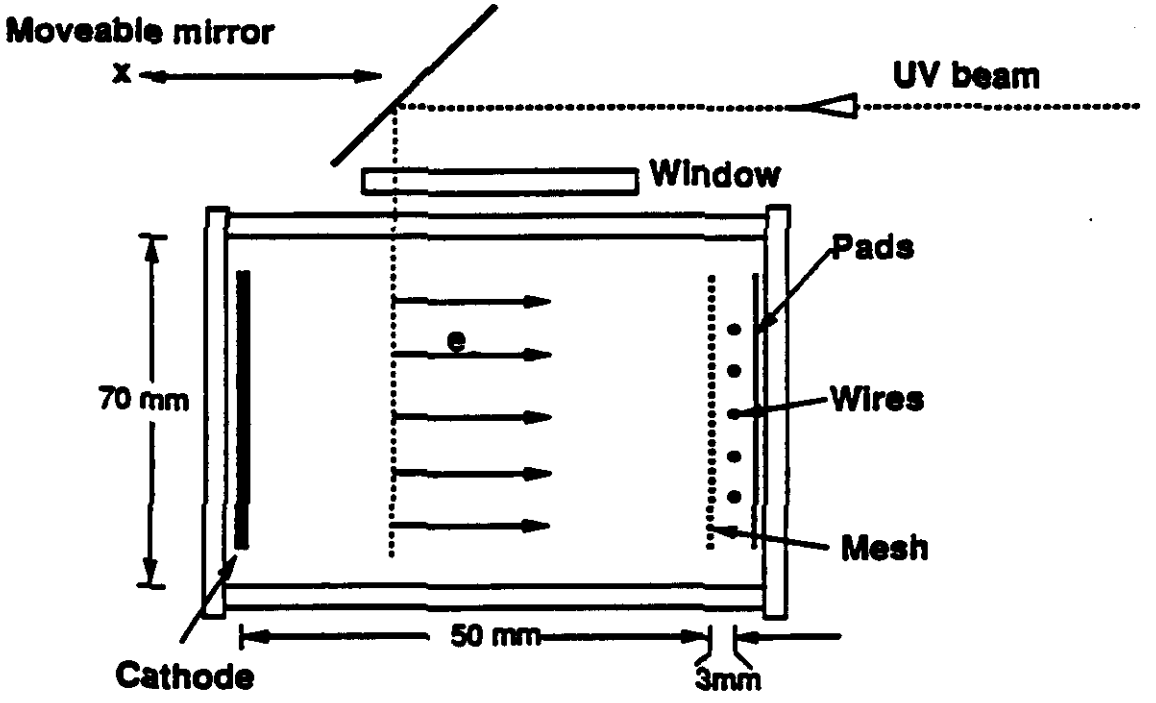
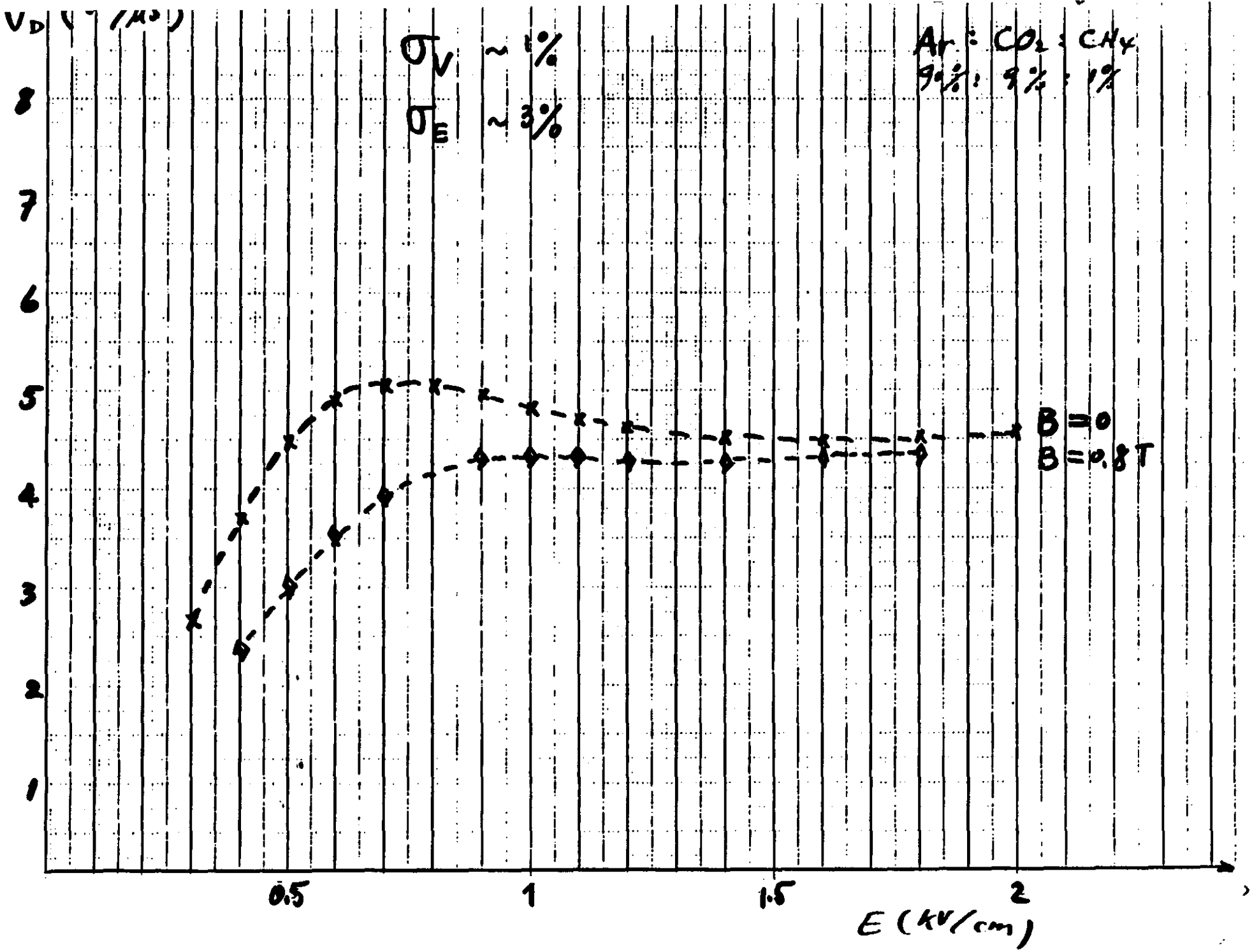
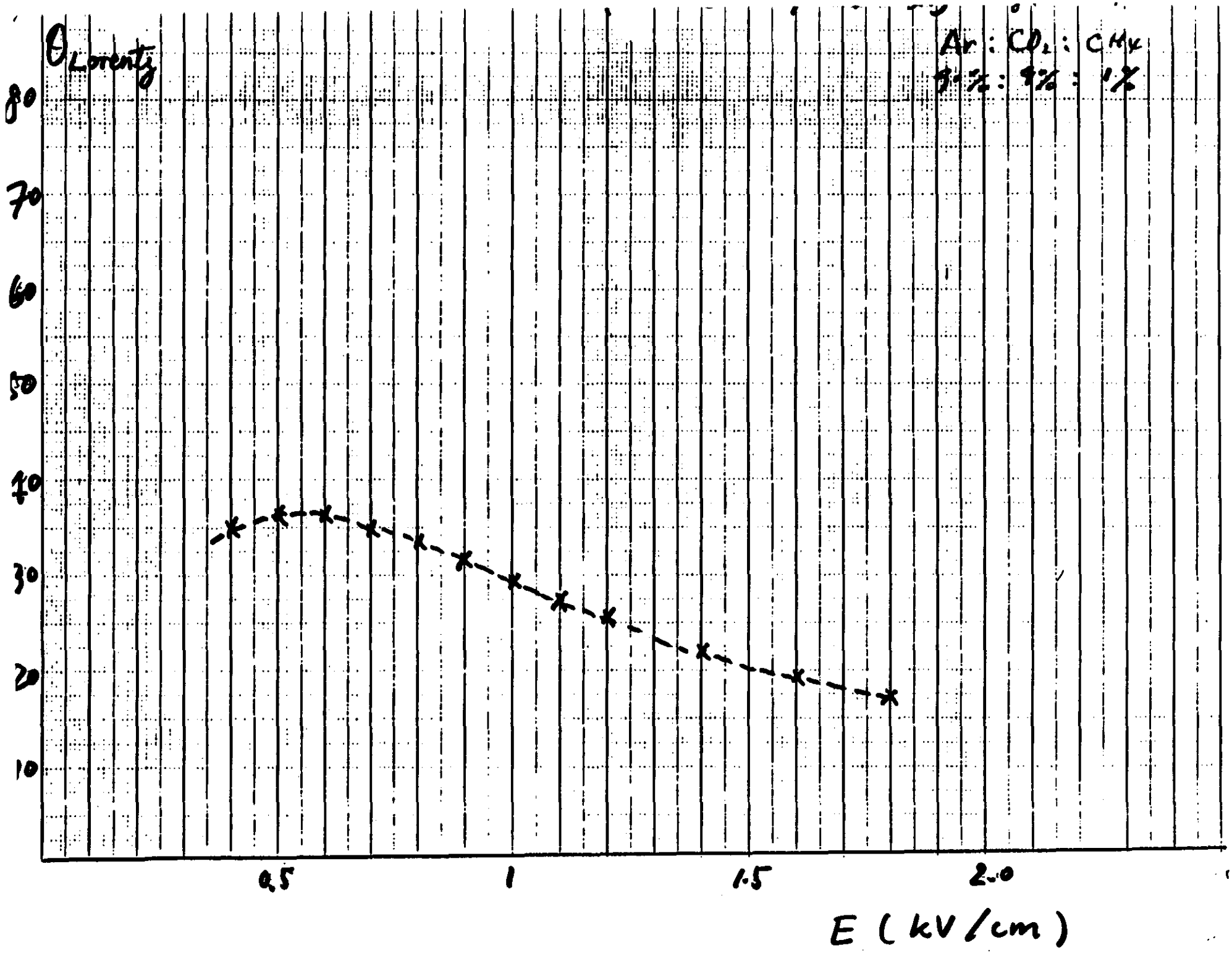

Moveable mirror
x
UV beam
Window
Pads
e
70 mm
Wires
Mesh
50 mm
Cathode
3mm

Fig. 1


V_D (μs)
$\sigma_V \sim 1\%$
$\sigma_E \sim 3\%$
Ar : CO_2 : CH_4
B = 0
B = 0.8 T
8
7
6
5
4
3
2
1
0.5
1
1.5
2
E (kV/cm)


$\theta_{Lorentz}$
Ar : CO_2 : CH_4
80
70
60
50
40
30
20
10
0.5
1
1.5
2.0
E (kV/cm)

Talk By Roy Weinstein on
Limited Streamer Tubes

recall

PDT Subsystem R&D Plans

Necessary R&D before LoI :

- **HRS octant (2) test:** wire tension after 10 years; alignment scheme; sagitta systematic error.

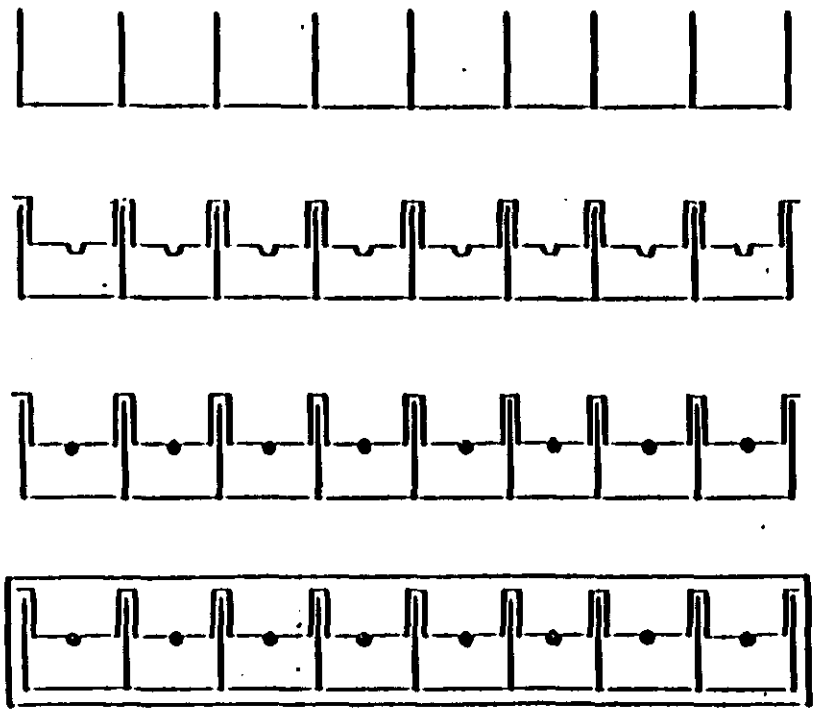
- **Pressurized drift tube modul ptototype.**

- **RPC prototype, z-chamber selection.**

- **Drift gas studies with magnetic field:** drift velocities, Lorentz angles and space-time functions.

- **Intensive simulations:** end-cap chamber design; muon trigger issues; pattern studies in inner chamber.

- **Alignment scheme design.**



a. 8-cell open profile
(Extruded PVC)

b. 8-fold wire holder
(Thermoset PVC)

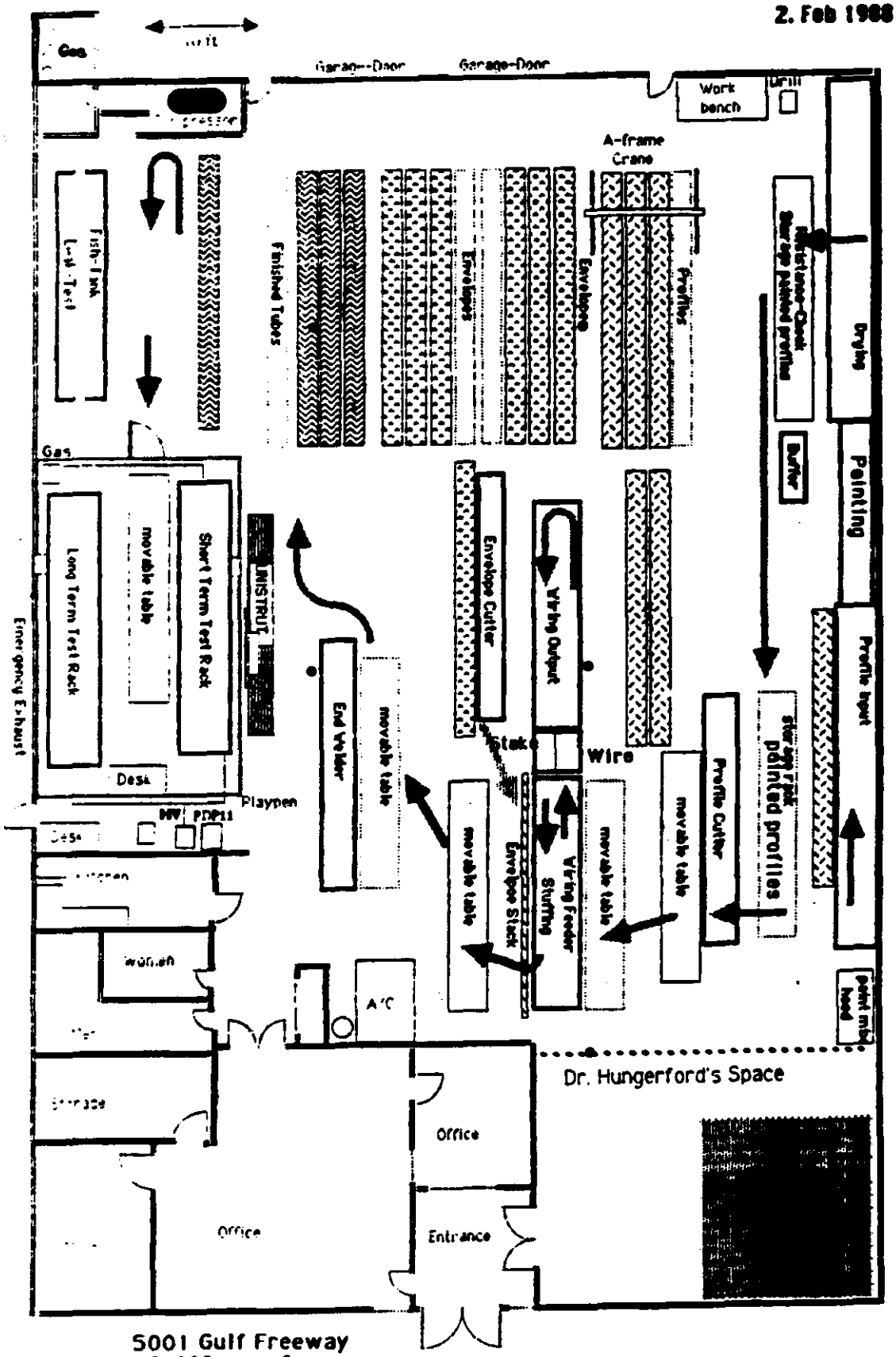
c. 100 μm Be-Cu wires

d. PVC cover

Figure II.B.4

Streamer Chamber Assembly

2. Feb 1988



5001 Gulf Freeway
8,000 sq. ft.

SCARF

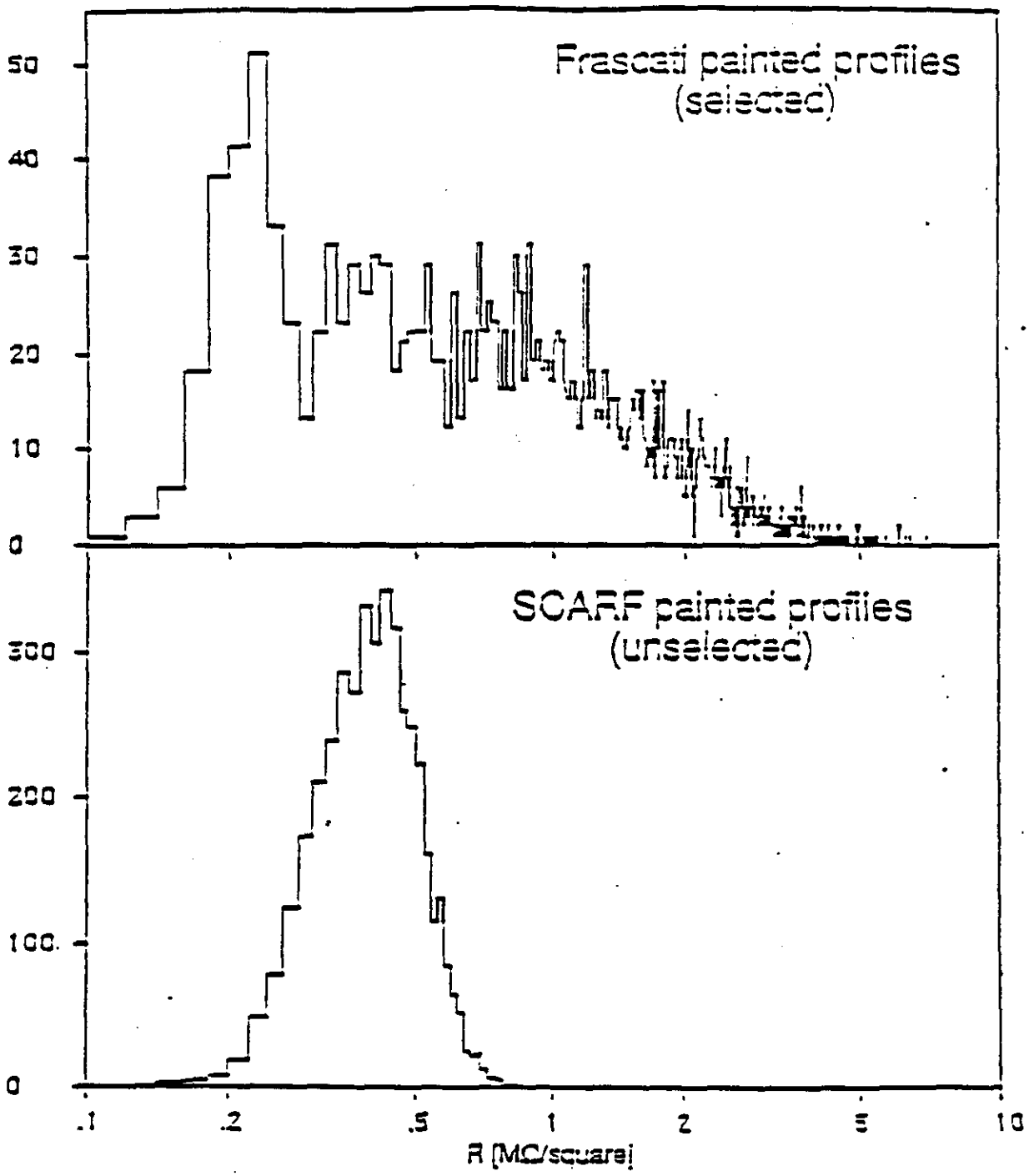
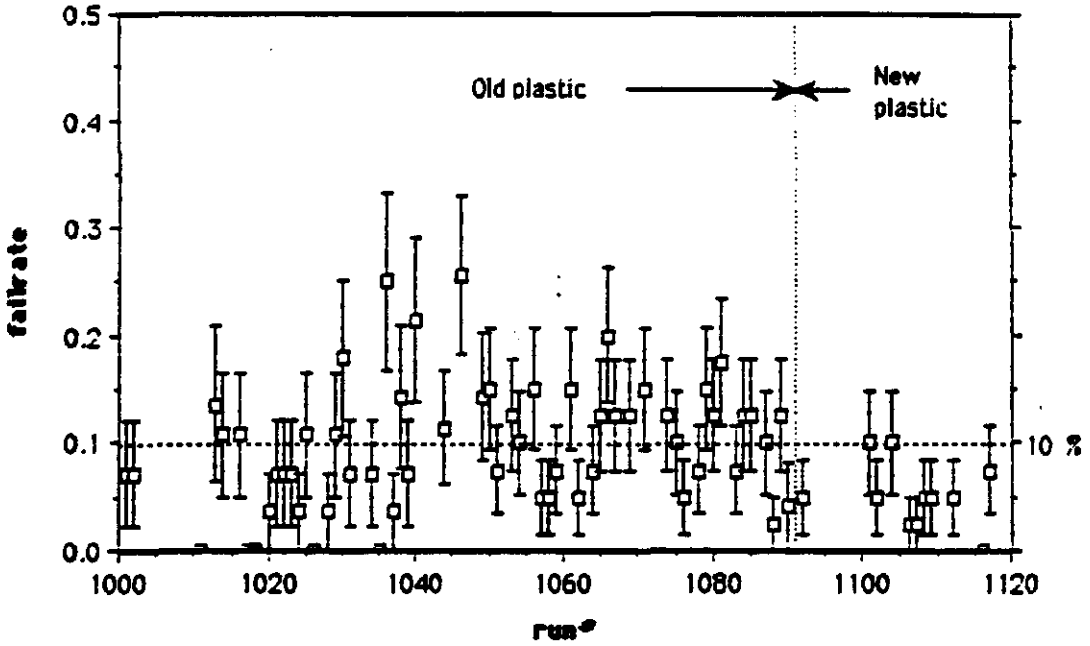
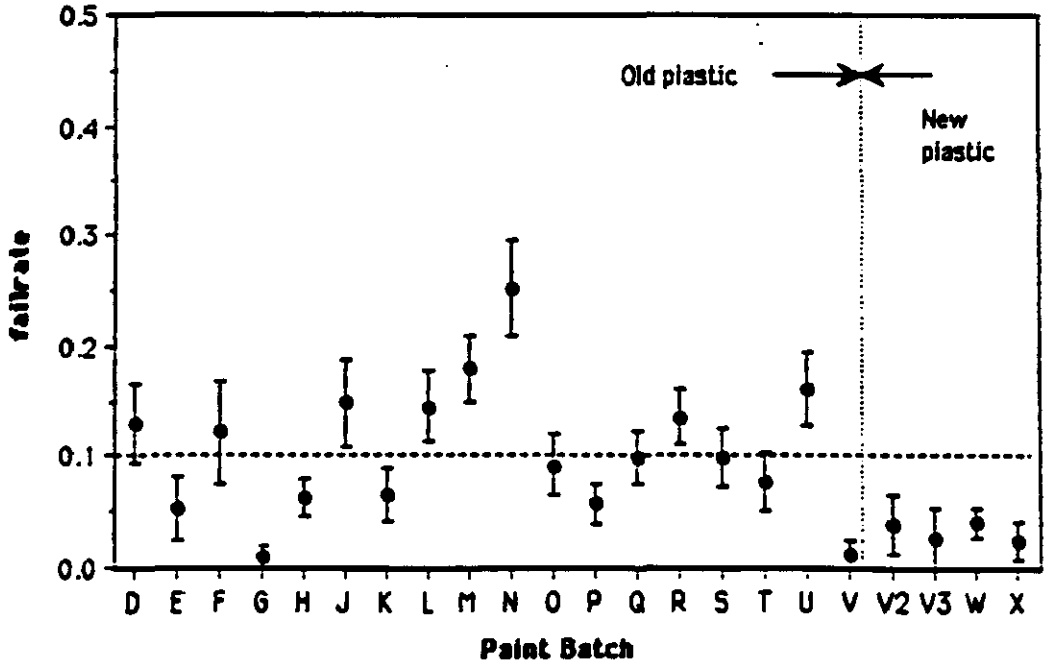


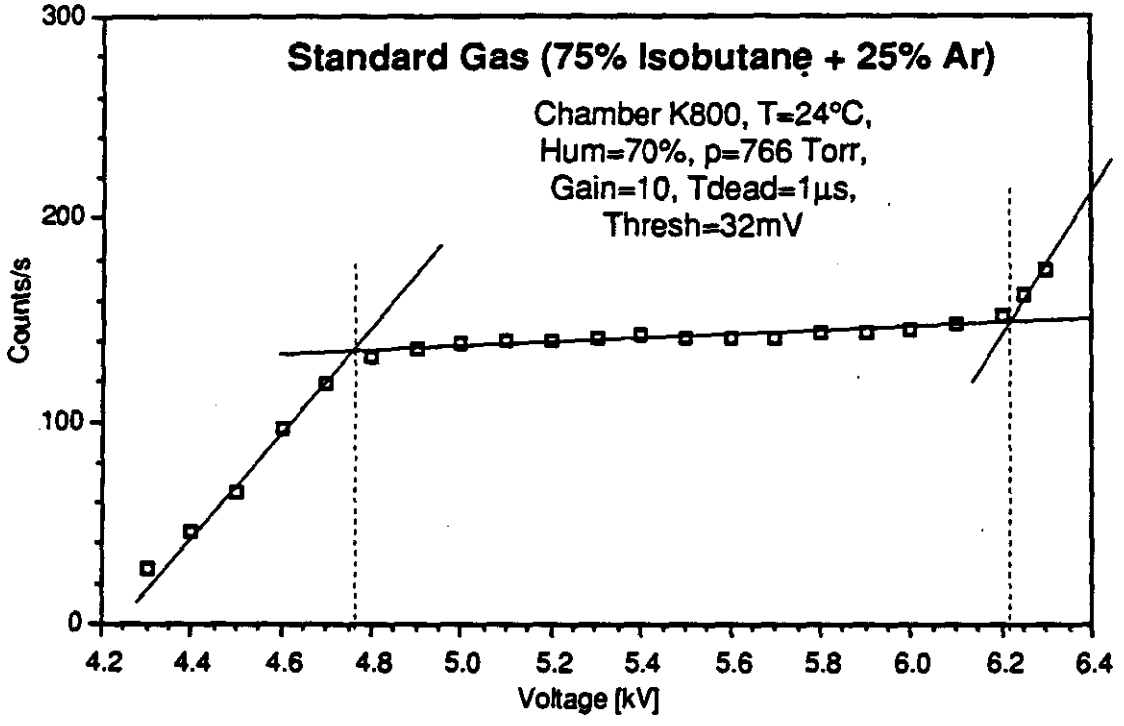
Fig. II.B.5. Resistance Spectra. Top: Frascati SLD accepted profiles. Selected by sampling R. About 50% rejected in this process. Bottom: SCARF profiles. R is sampled for comparison only. 100% of coated profiles are used.

Burnin Failures by Run# 9-6-88



Burnin Failures by Paint-batch




Standard Gas (75% Isobutane + 25% Ar)
Chamber K800, T=24°C,
Hum=70%, p=766 Torr,
Gain=10, Tdead=1µs,
Thresh=32mV
Counts/s
300
200
100
0
4.2
4.4
4.6
4.8
5.0
5.2
5.4
5.6
5.8
6.0
6.2
6.4
Voltage [kV]

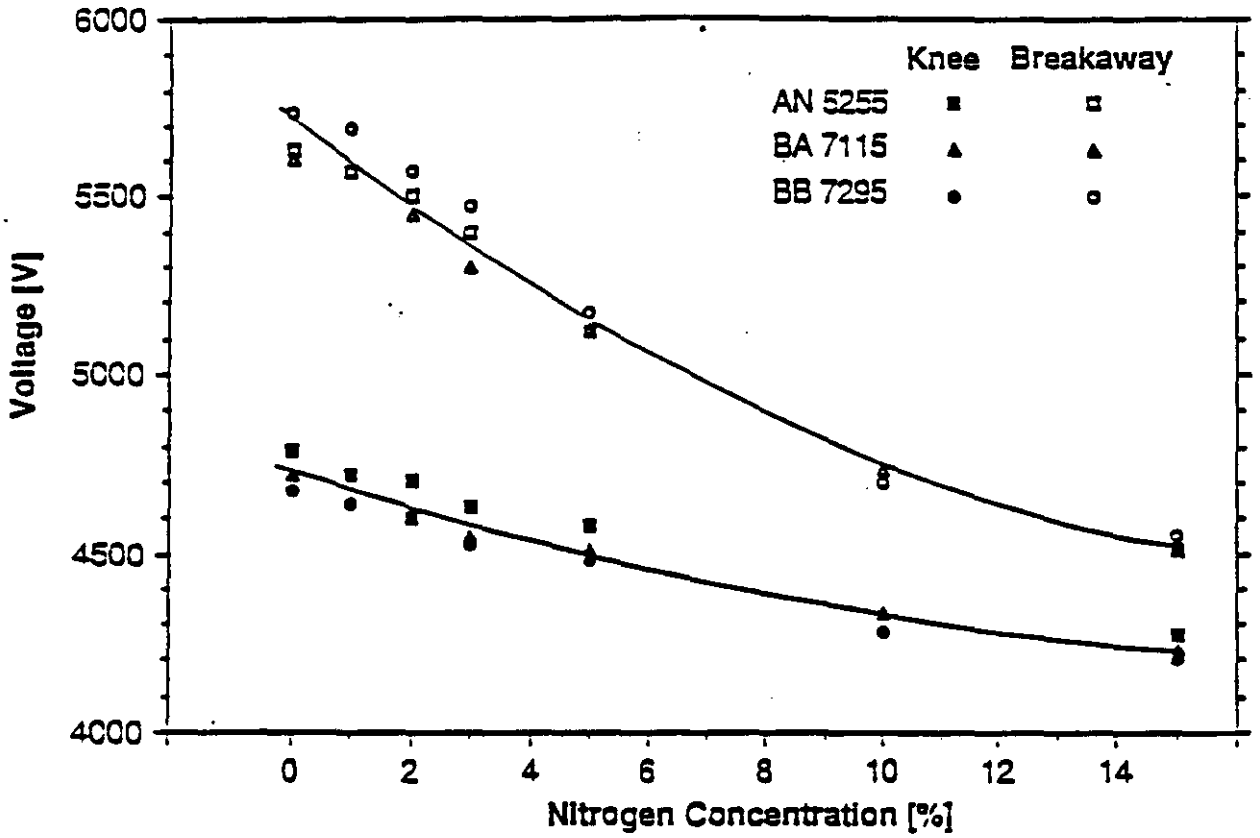
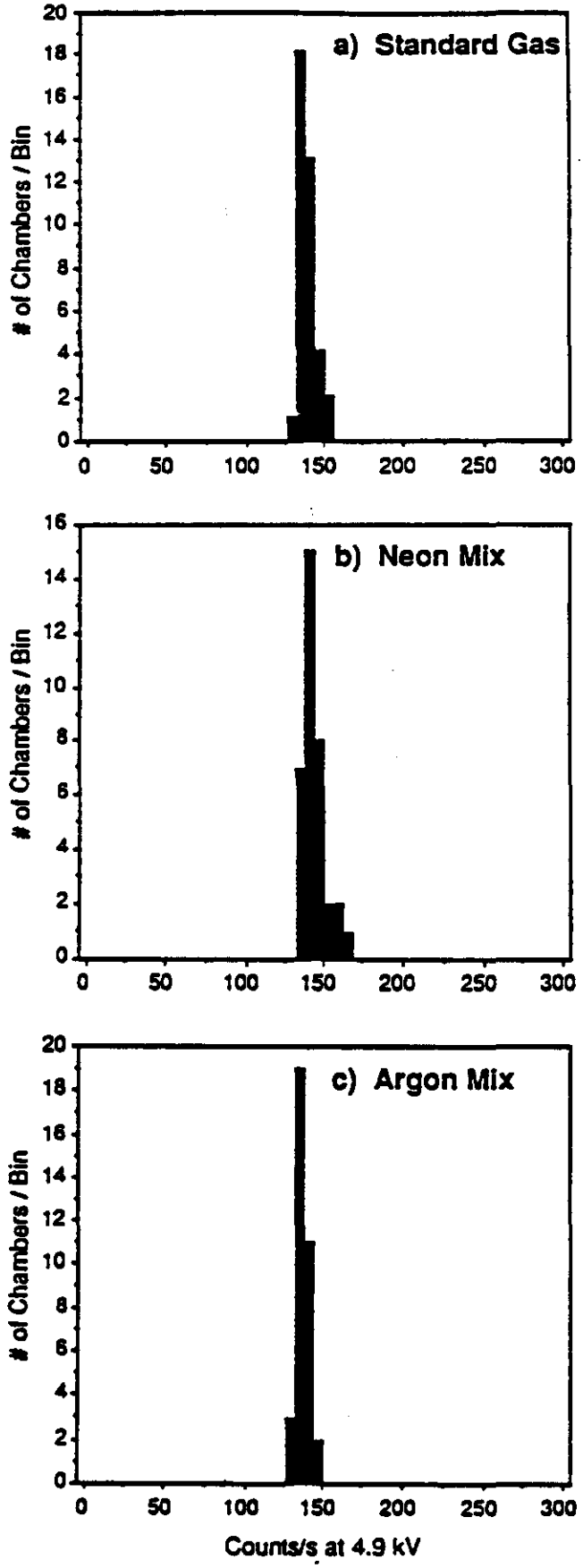
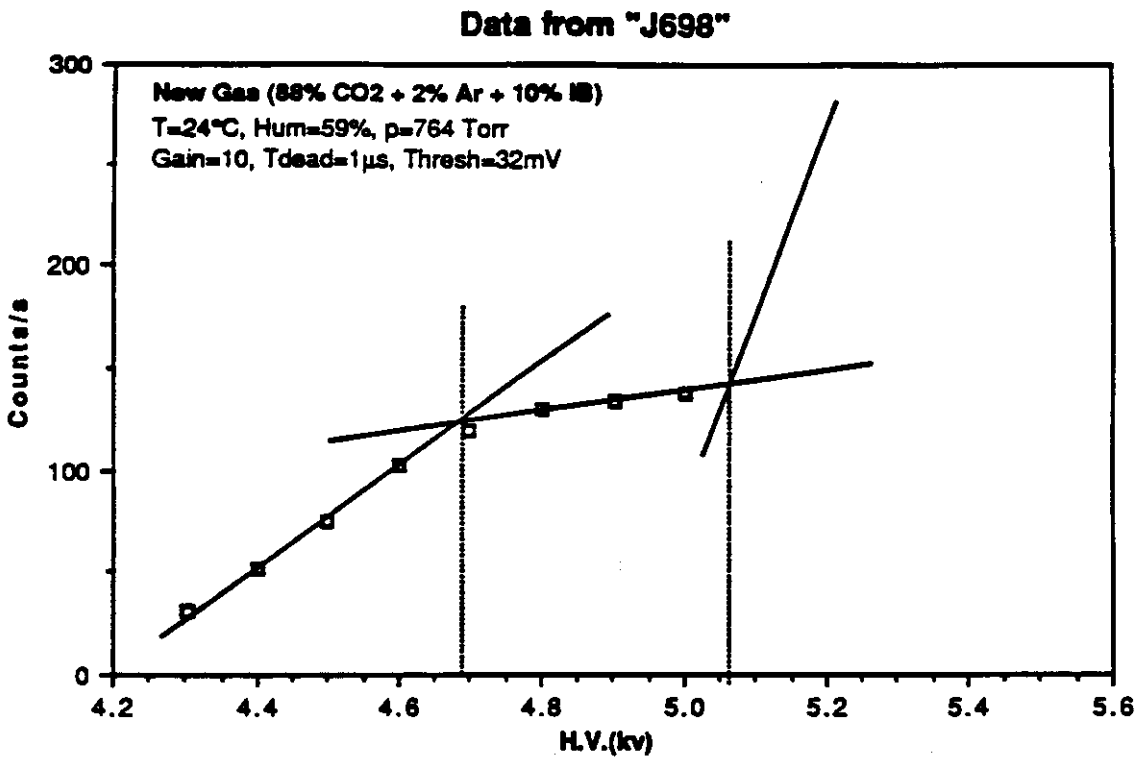
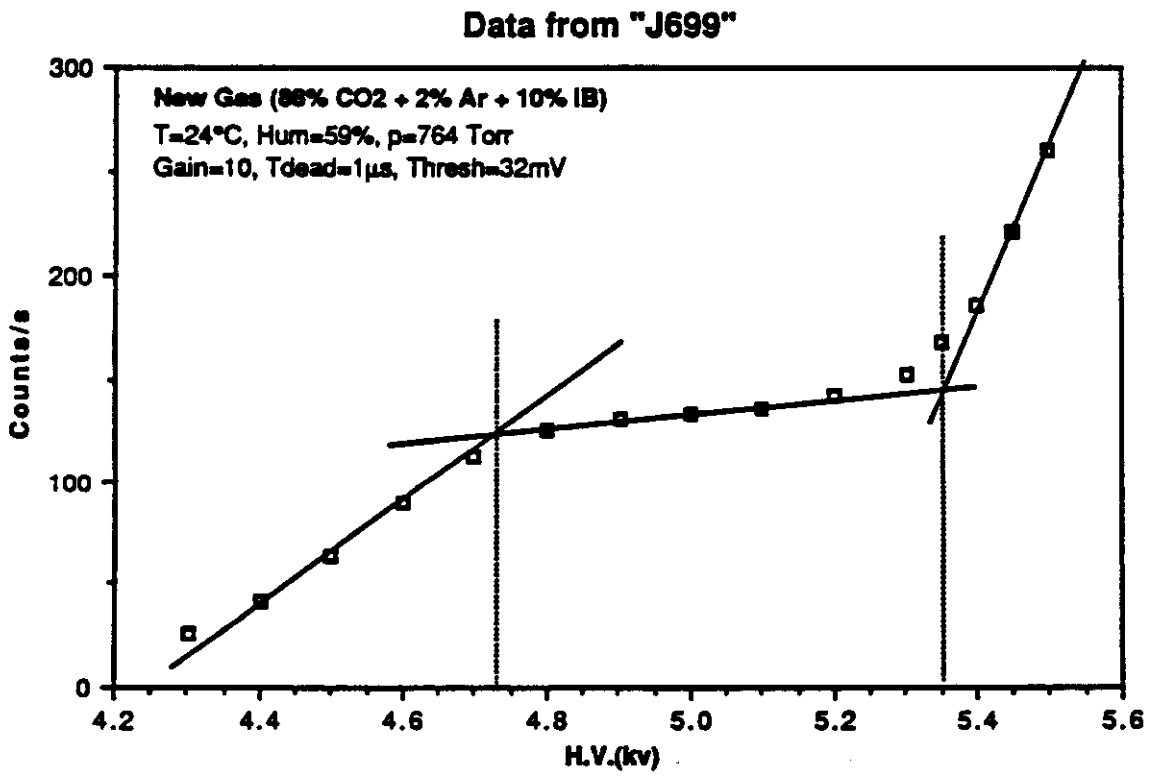
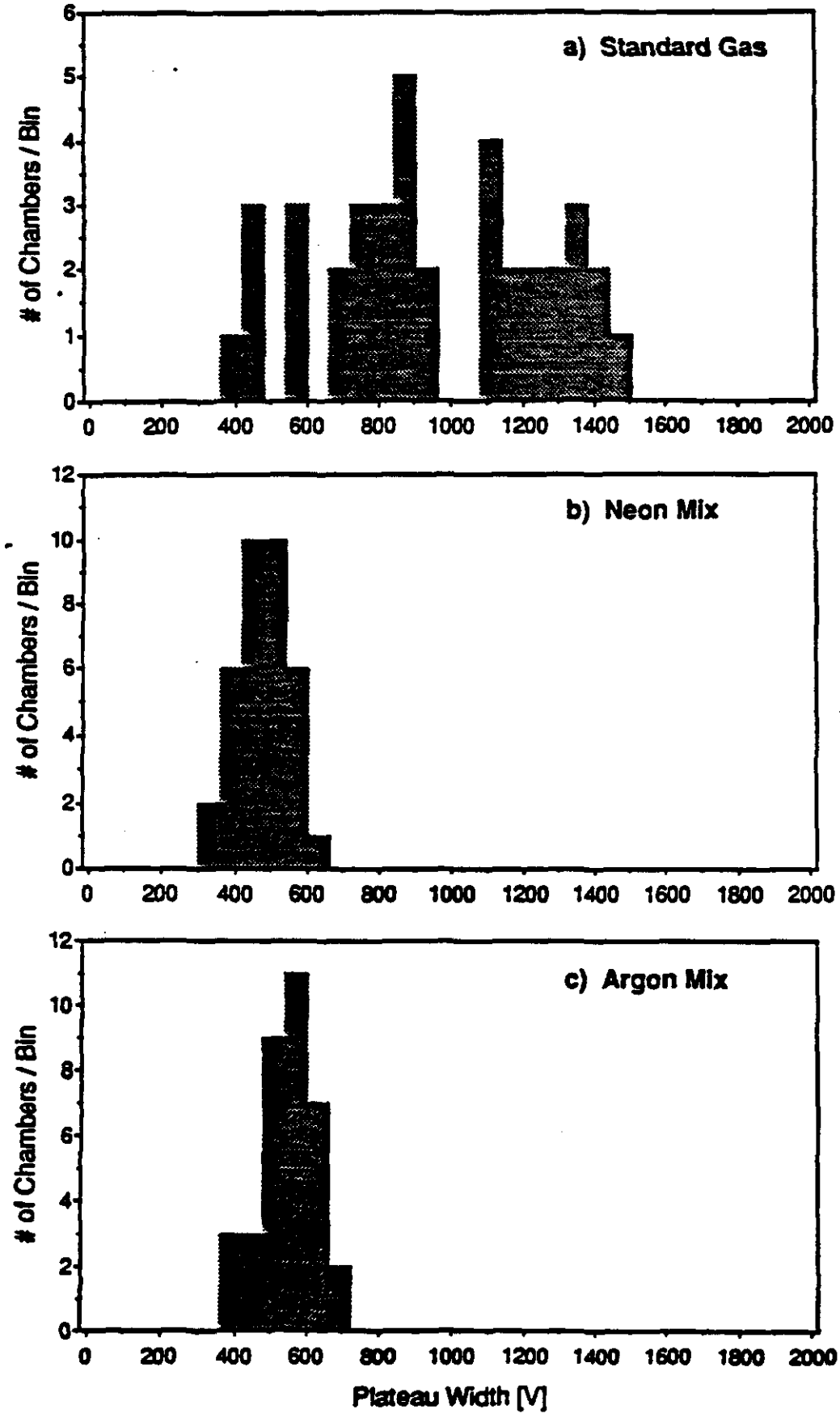


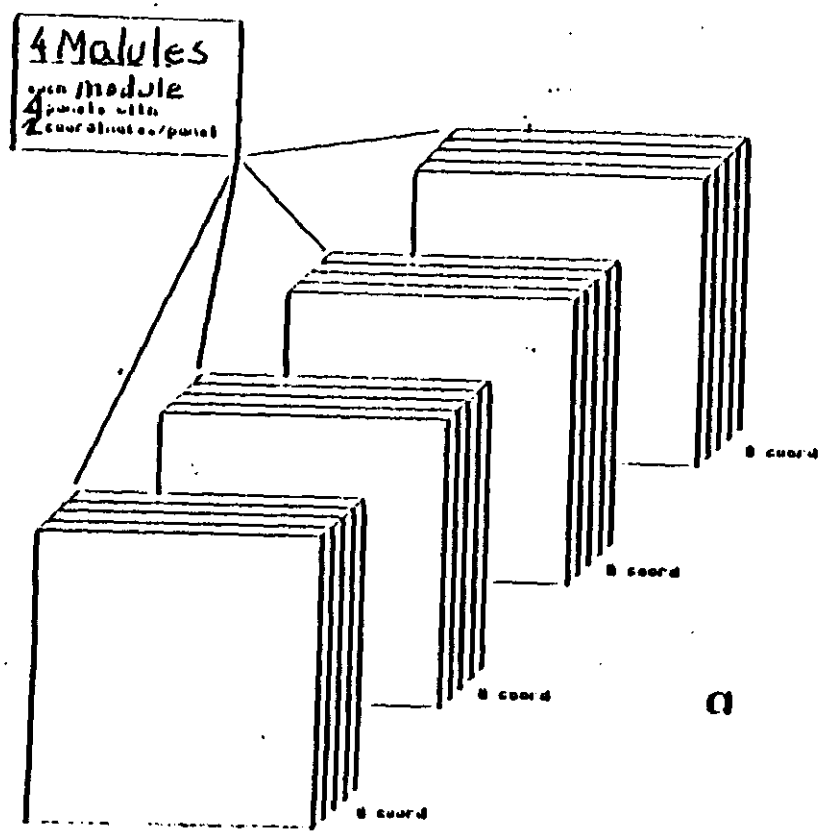
Fig. II.B.1. Effect of Nitrogen Contamination. Plateau at any % Nitrogen is top (open) point minus bottom (filled) point. Plateau not only narrows, but moves to lower HV.


a) Standard Gas
b) Neon Mix
c) Argon Mix
# of Chambers / Bin
Counts/s at 4.9 kV
0
50
100
150
200
250
300


Data from "J698"
New Gas (88% CO2 + 2% Ar + 10% IB)
T=24°C, Hum=59%, p=764 Torr
Gain=10, Tdead=1µs, Thresh=32mV
Counts/s
H.V.(kv)
0
100
200
300
4.2
4.4
4.6
4.8
5.0
5.2
5.4
5.6


Data from "J699"
New Gas (88% CO2 + 2% Ar + 10% IB)
T=24°C, Hum=59%, p=764 Torr
Gain=10, Tdead=1µs, Thresh=32mV
Counts/s
H.V.(kv)
0
100
200
300
4.2
4.4
4.6
4.8
5.0
5.2
5.4
5.6


a) Standard Gas
b) Neon Mix
c) Argon Mix
# of Chambers / Bin
Plateau Width [V]
0
200
400
600
800
1000
1200
1400
1600
1800
2000



32 coordinates total

new muon chambers ST6/7 built from streamer tubes

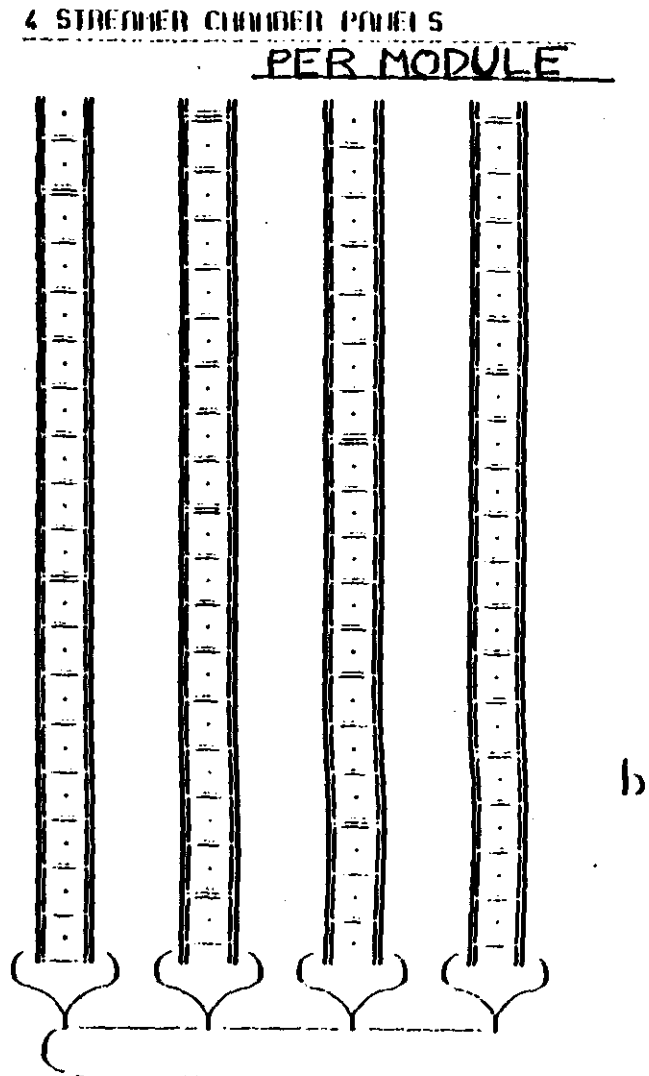


FIG II.A.1.

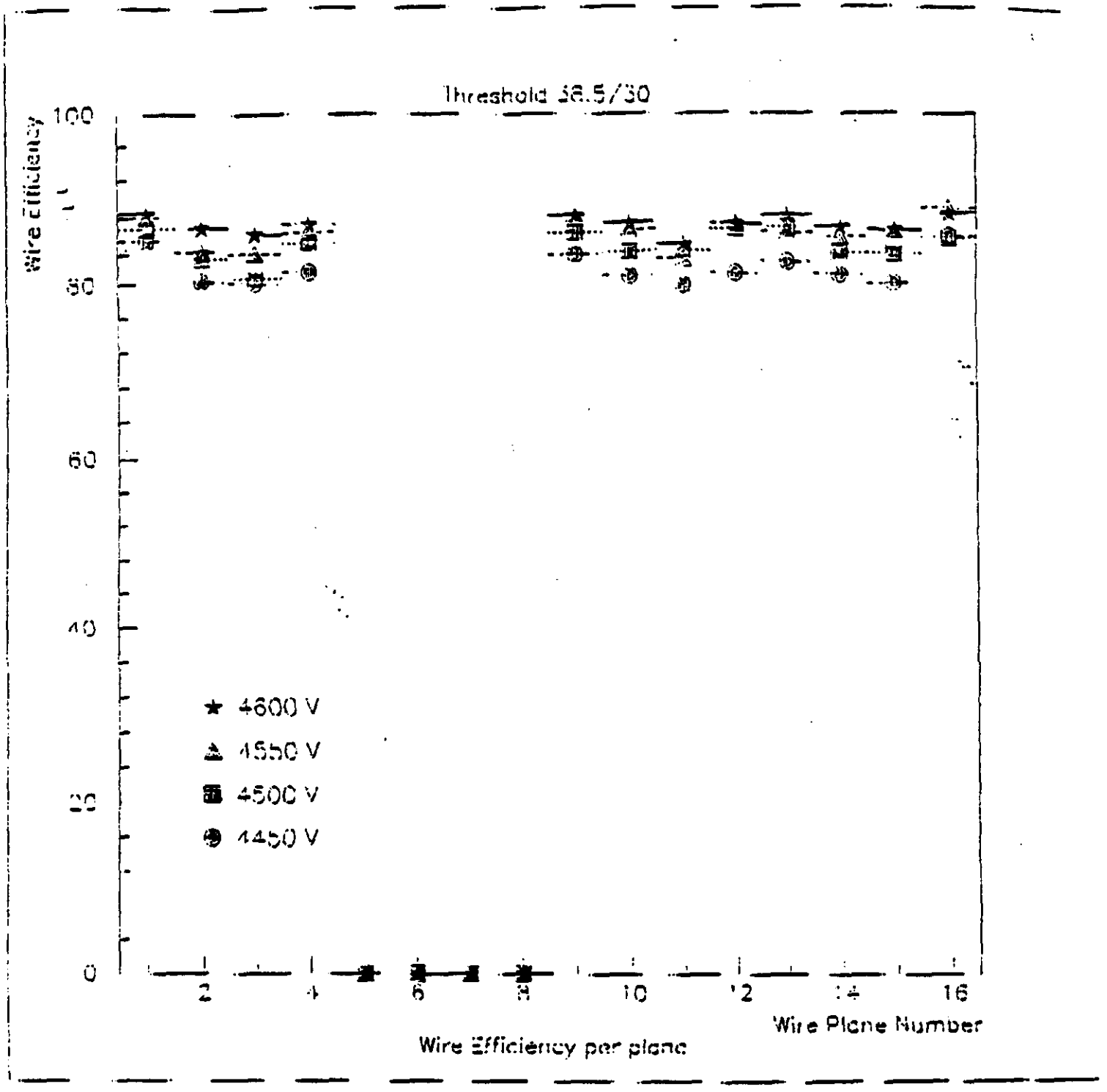


Figure * (Graph added in proof 08/14/91)**
Single plane efficiency of modules A,C,&D (12 planes).
Note best theoretical estimate of single plane efficiency is 83%

Talk by Andrey Korytov
on Fermilab Beam Tests of
Limited Streamer Tubes

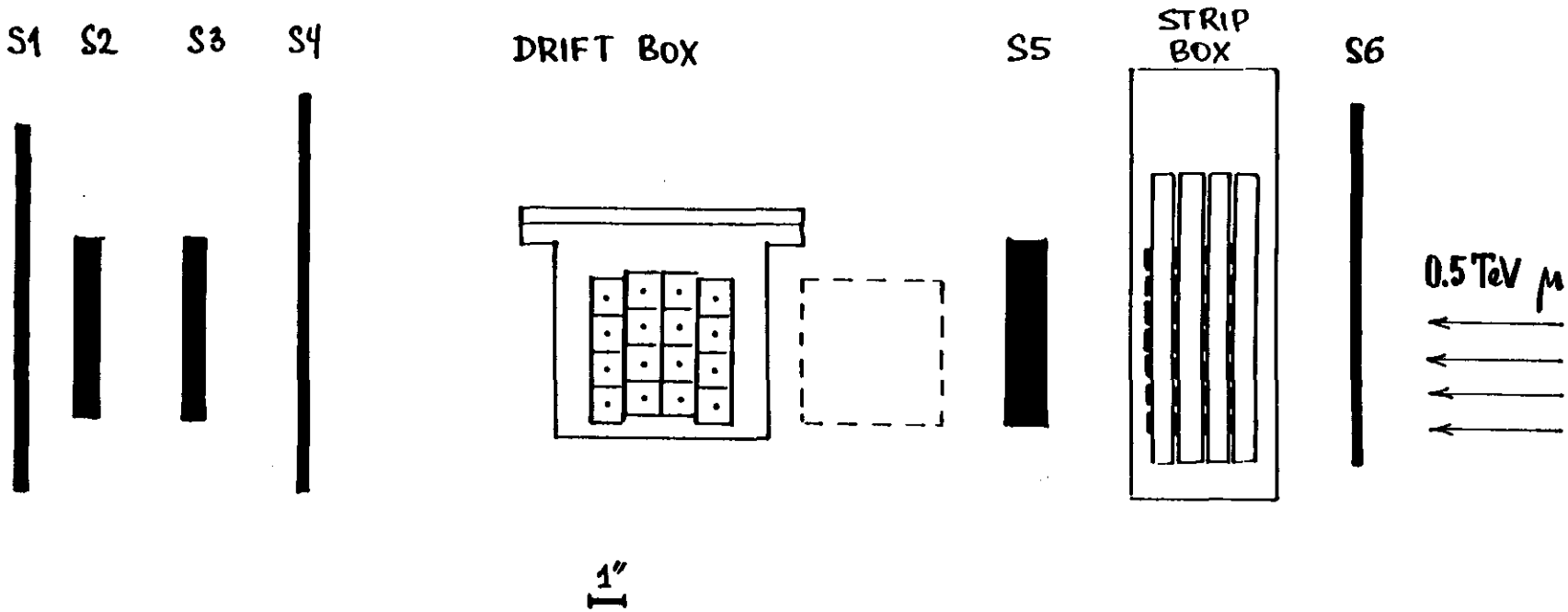
Aug 23, 1991: STATUS OF MUON TESTS at FERMILAB

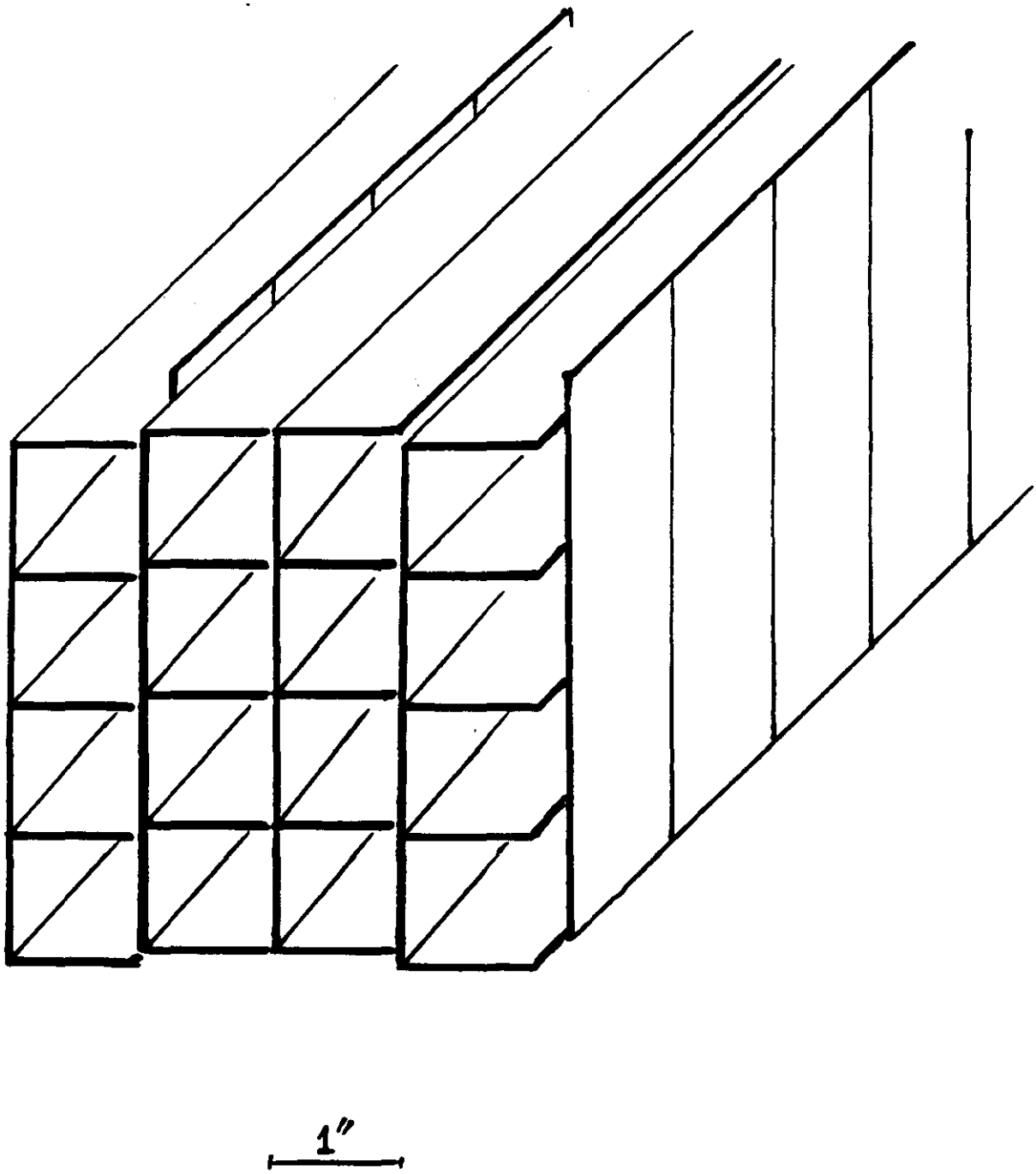
PURPOSE:

1. LST's with DRIFT READOUT
   (resolution vs gas, H.V. etc...)

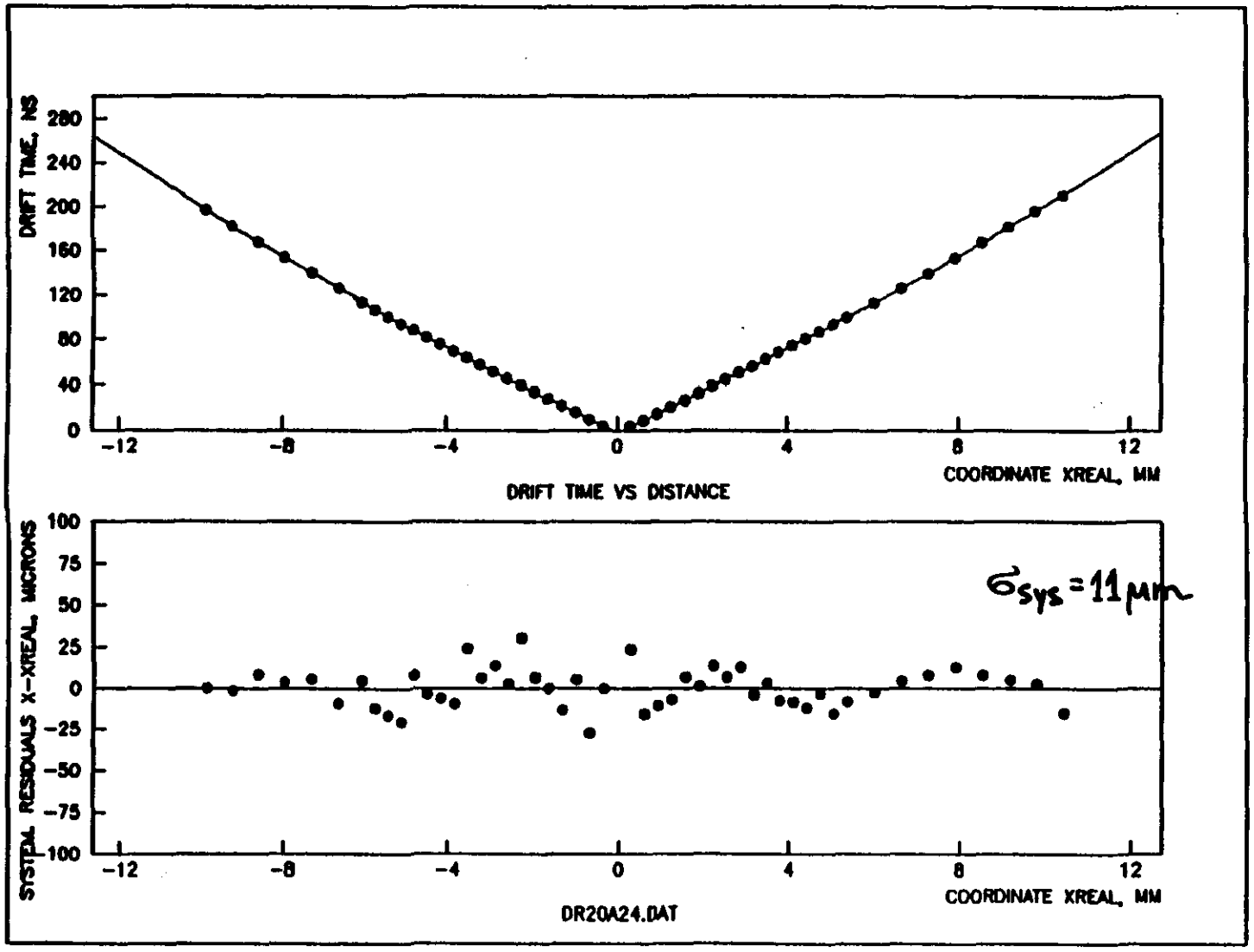
2. Iarocci Tubes with STRIP READOUT
   (resolution vs SQS-PROP. Modes, α ...)

3. Influence of e.m. debris generated by muons on detector performance

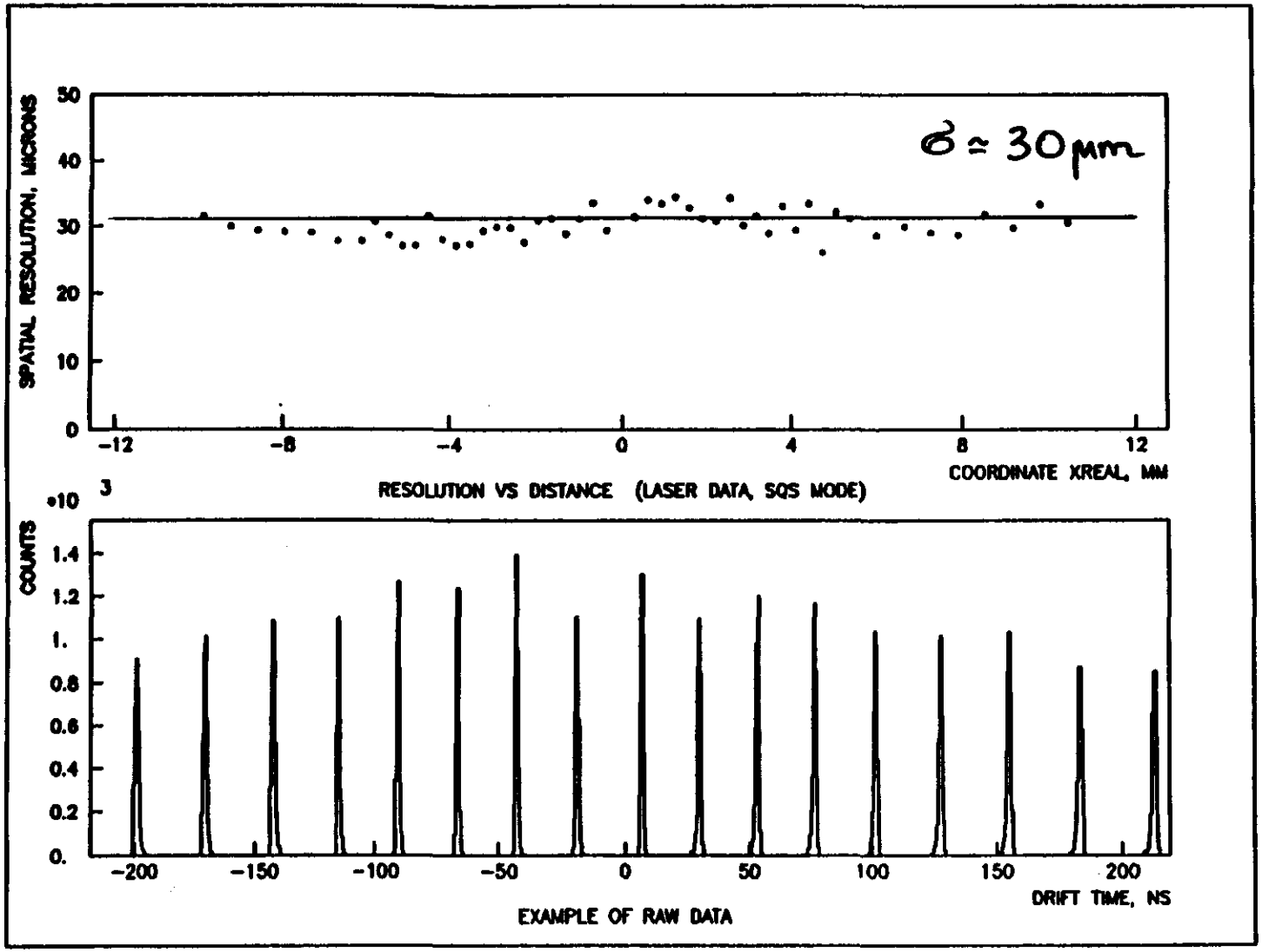

S1
S2
S3
S4
DRIFT BOX
S5
STRIP BOX
S6
0.5 TeV μ
1"

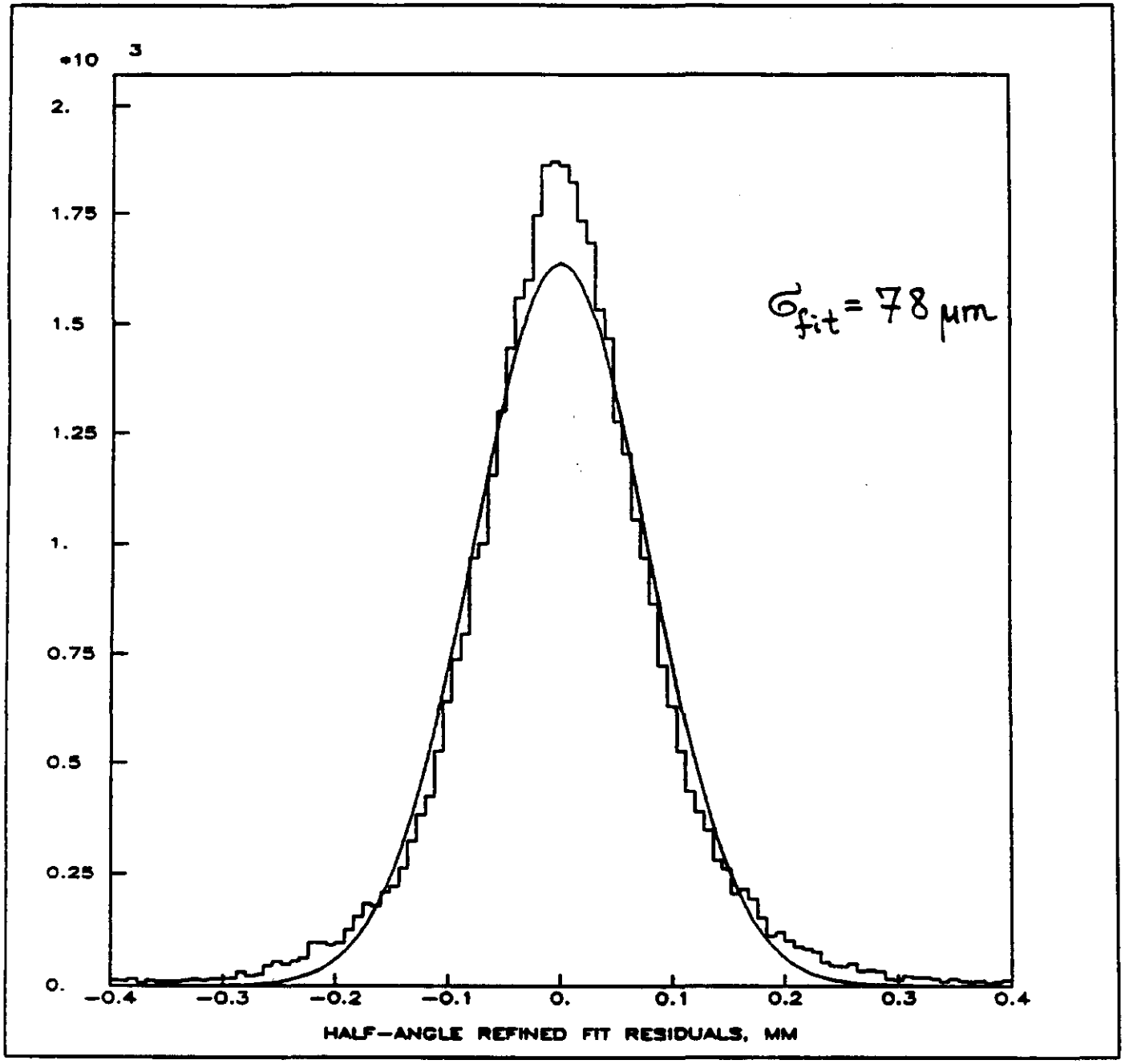

1″

$Ar + C_4H_{10} = 1+3$
SQS mode
Laser Data

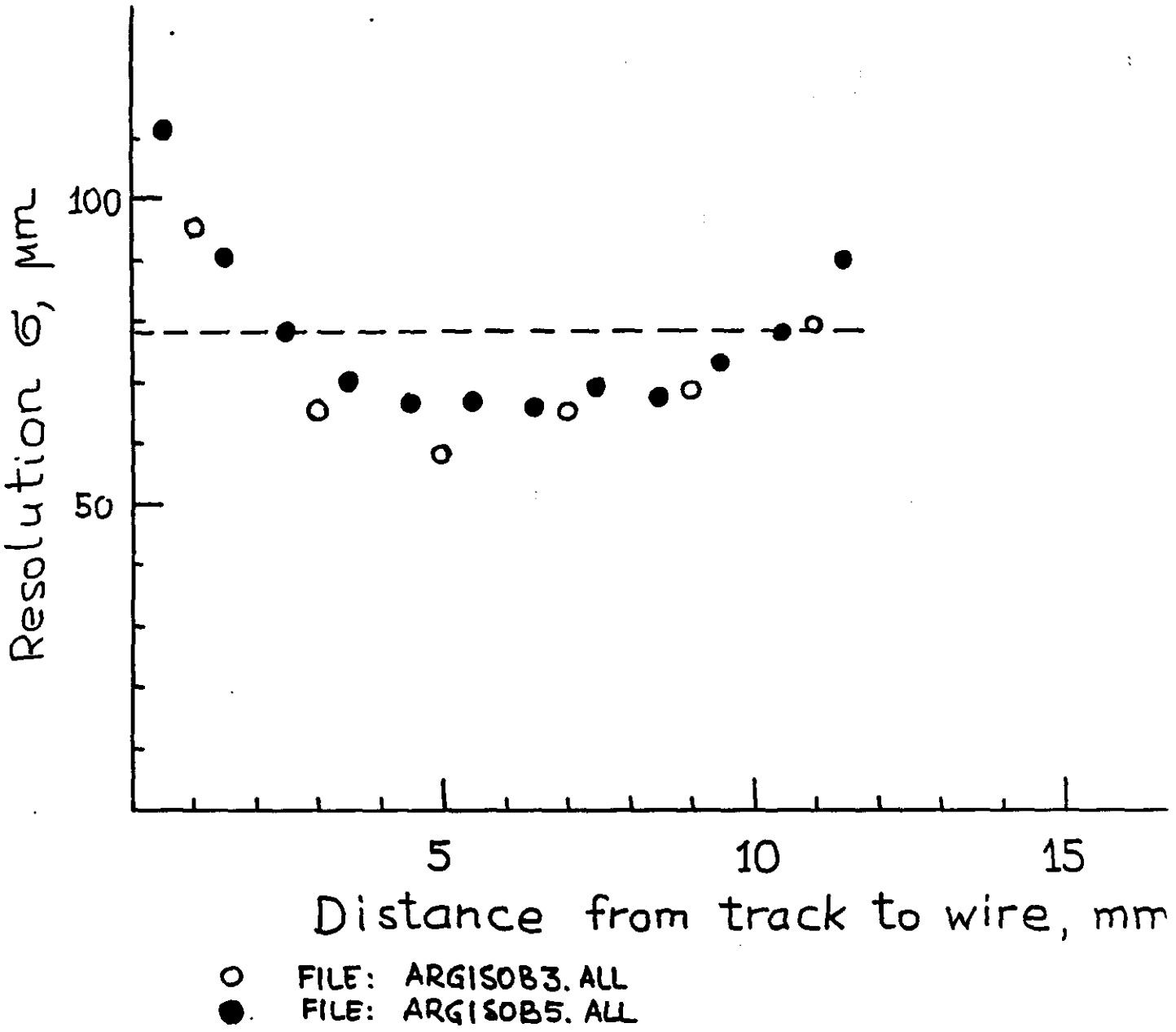


$Ar + C_4H_{10} = 1+3$
SQS mode
LASER DATA

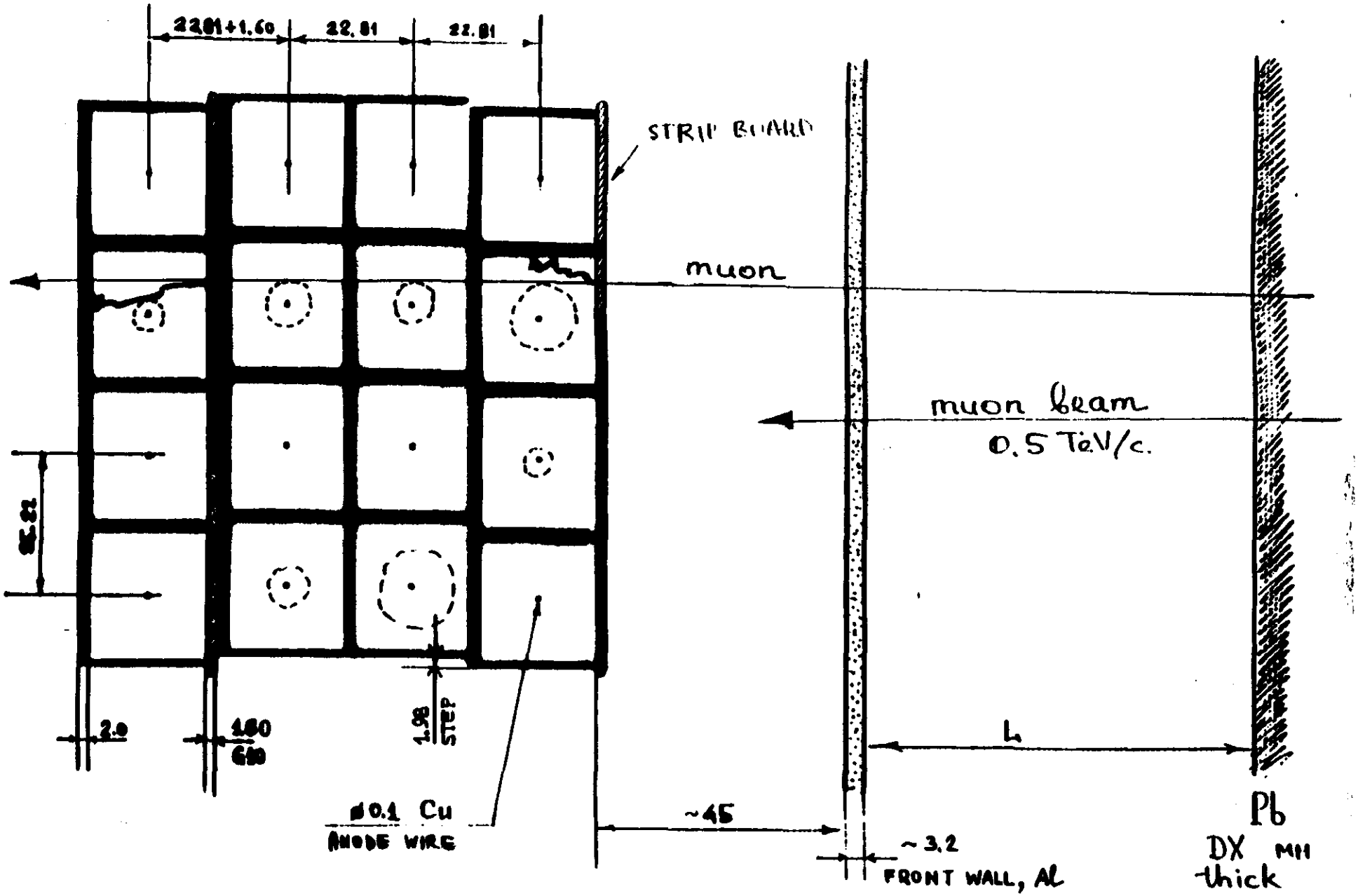


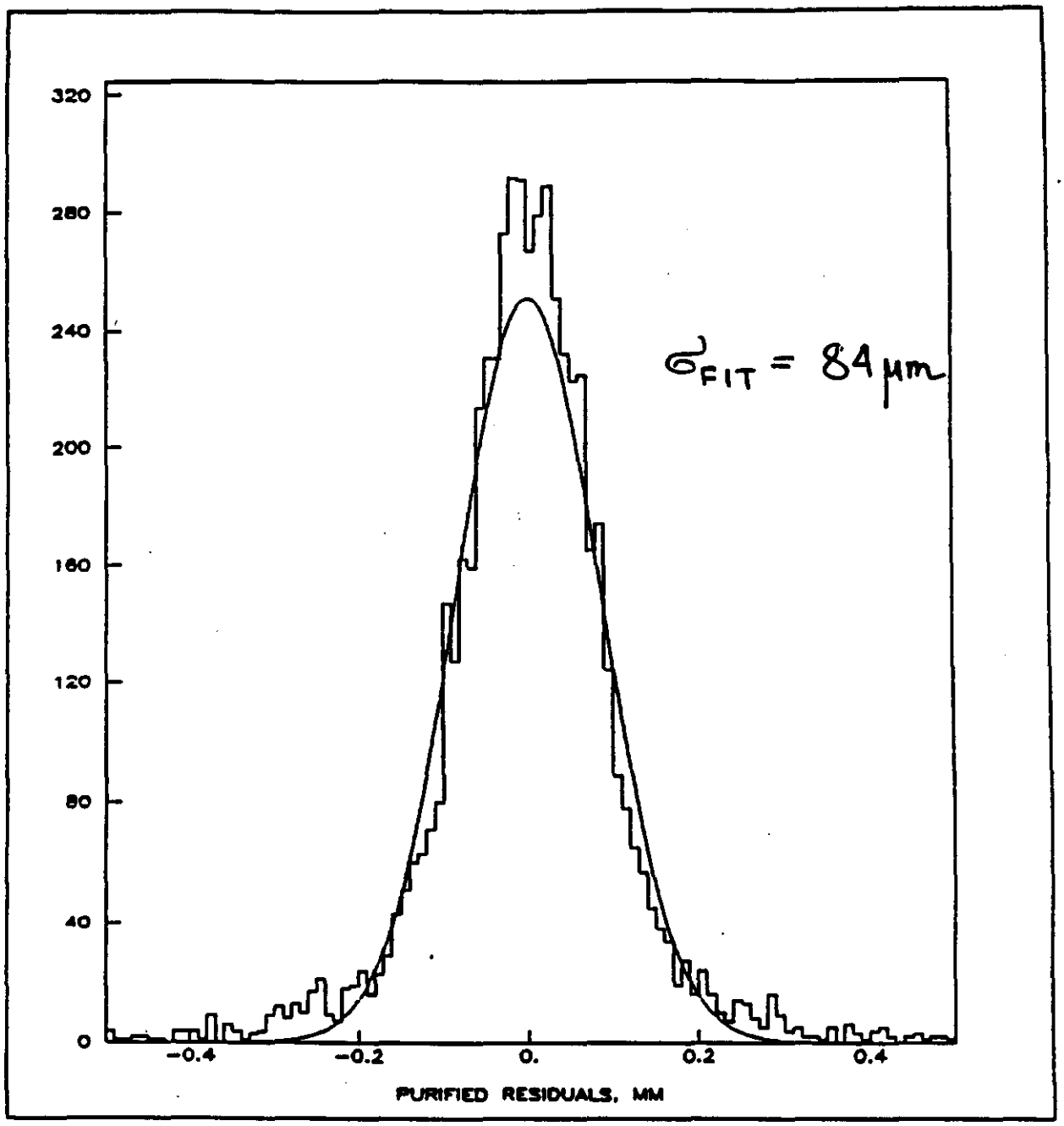


$Ar + C_4H_{10} = 1+3$, SQS mode
cosmic rays data



$Ar + C_4H_{10} = 1+3$, SQS mode
cosmic rays data

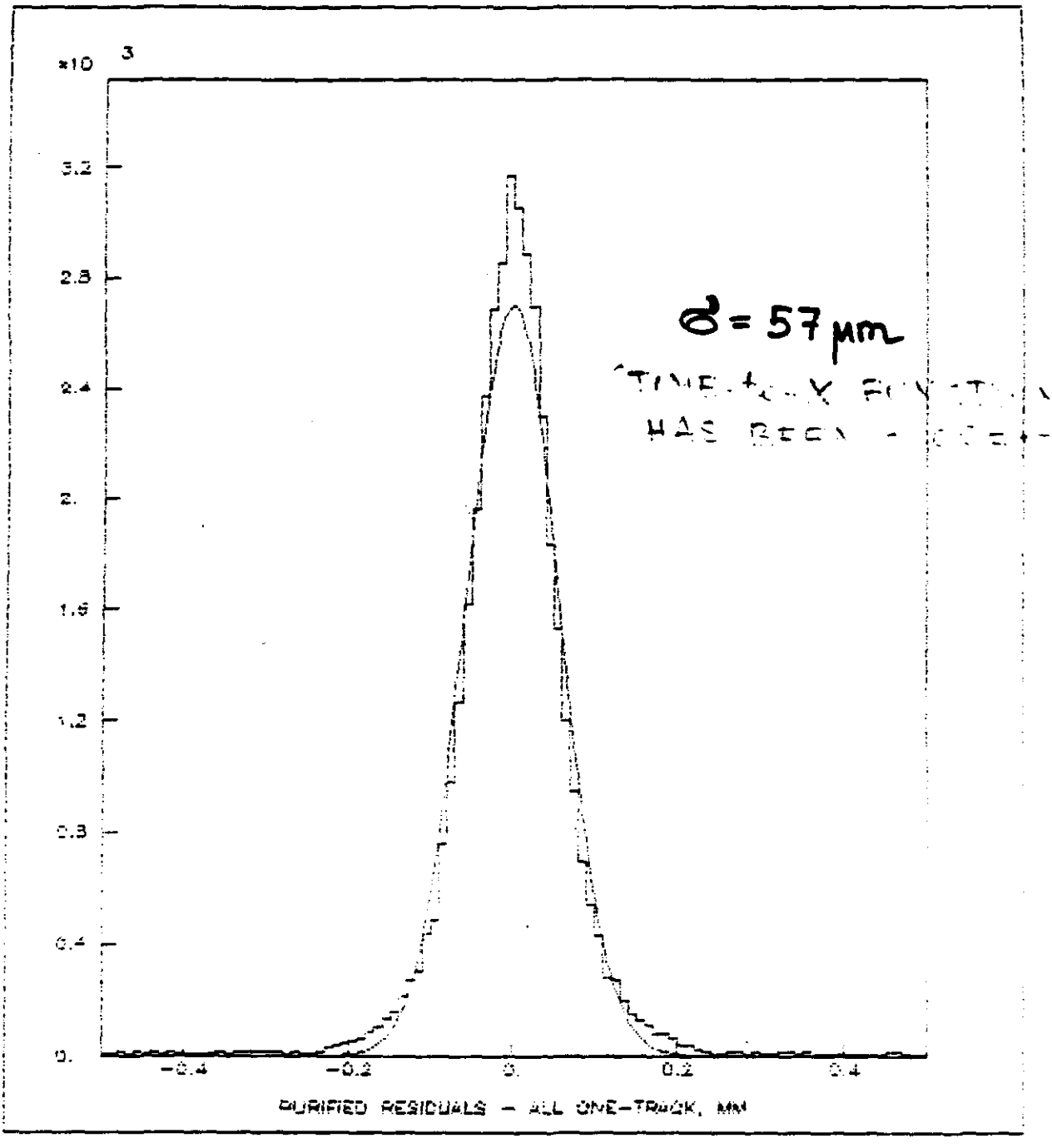

22.81+1.60
22.81
22.81
STRIP BOARD
muon
muon beam
0.5 TeV/c.
2.0
1.60
1.98
STEP
ø0.1 Cu
ANODE WIRE
~45
L
~3.2
FRONT WALL, Al
Pb
DX MH
thick



RUN-D001.DAT

ALL "ONE-TRACK" EVENTS
0.5 TeV/c MUONS

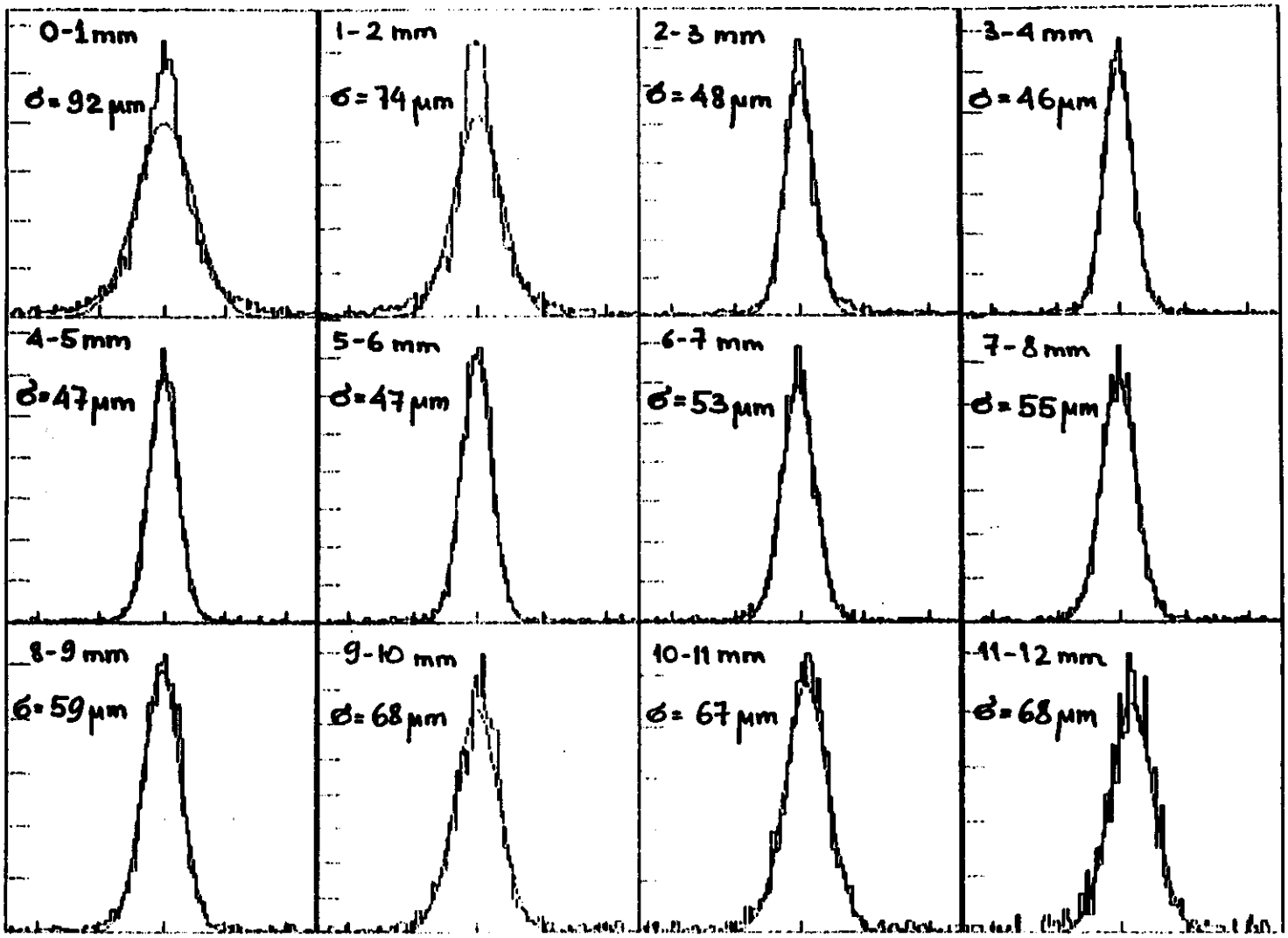
$Ar + C_4H_{10} = 1+3$
SQS mode



RUN-D012.DAT

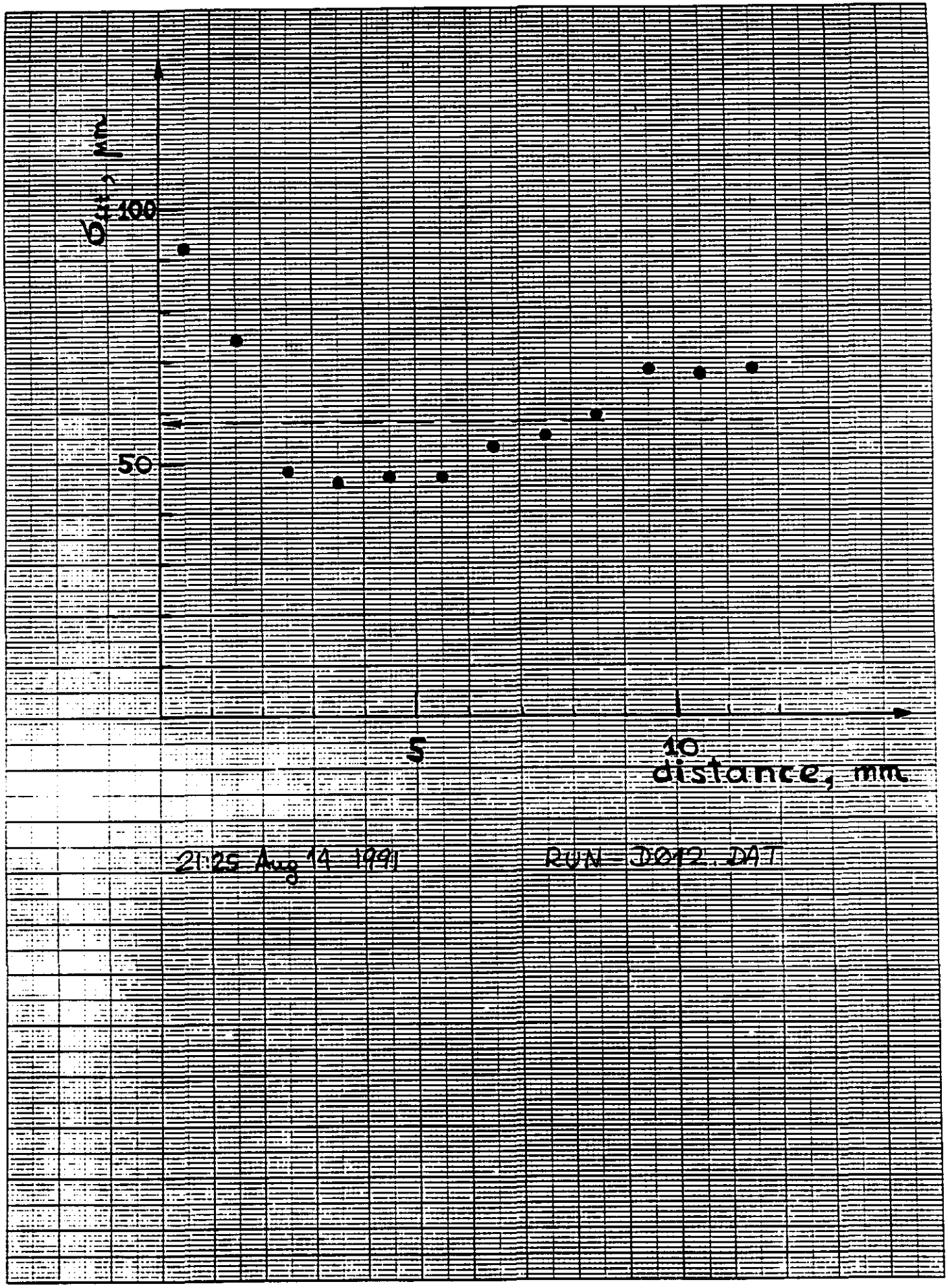
$Ar + C_4H_{10} = 1+3$ (SQS) Threshold = 15 mV

~0.5 TeV muons

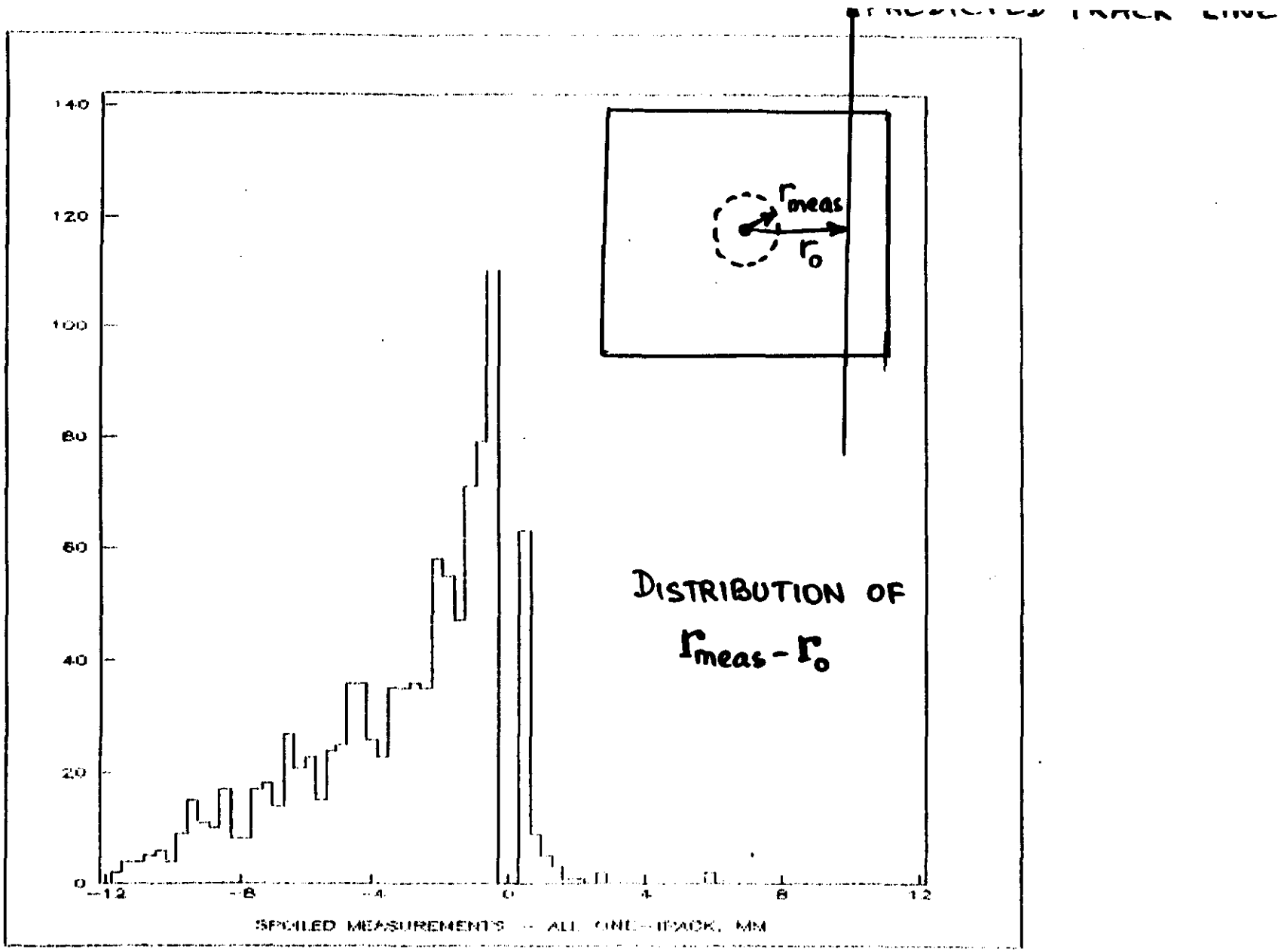


RUN-D012. DAT Ar+ C_4H_{10} = 1+3 SQS mode (5.4 kV) Threshold = 15 mV

~0.5 TeV/c muons



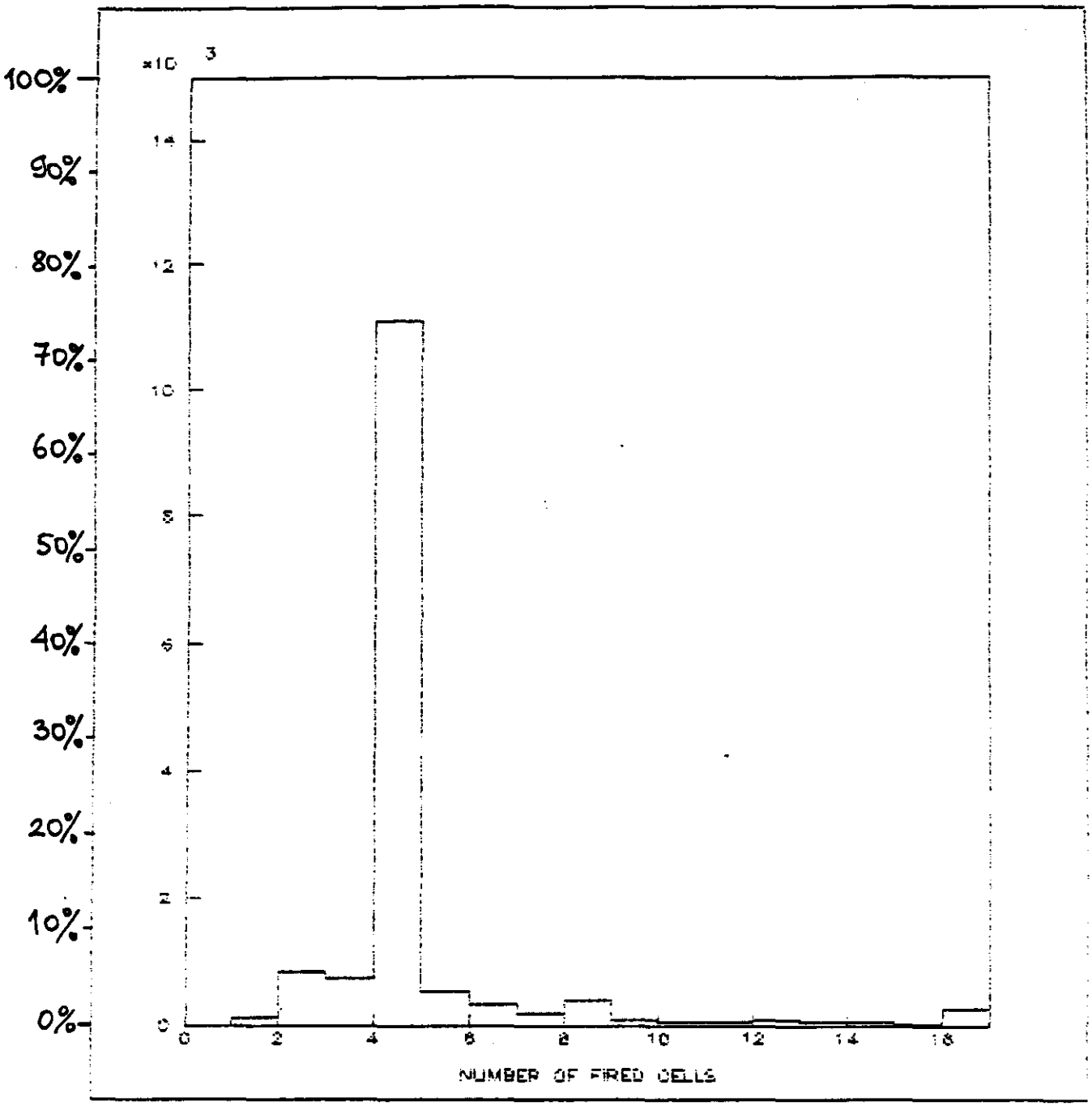
46 1510
K+E 10 X 10 TO THE CENTIMETER 18 X 25 CM
KEUFFEL & ESSER CO. MADE IN U.S.A.



DATA with ONLY ONE spoiled measurement

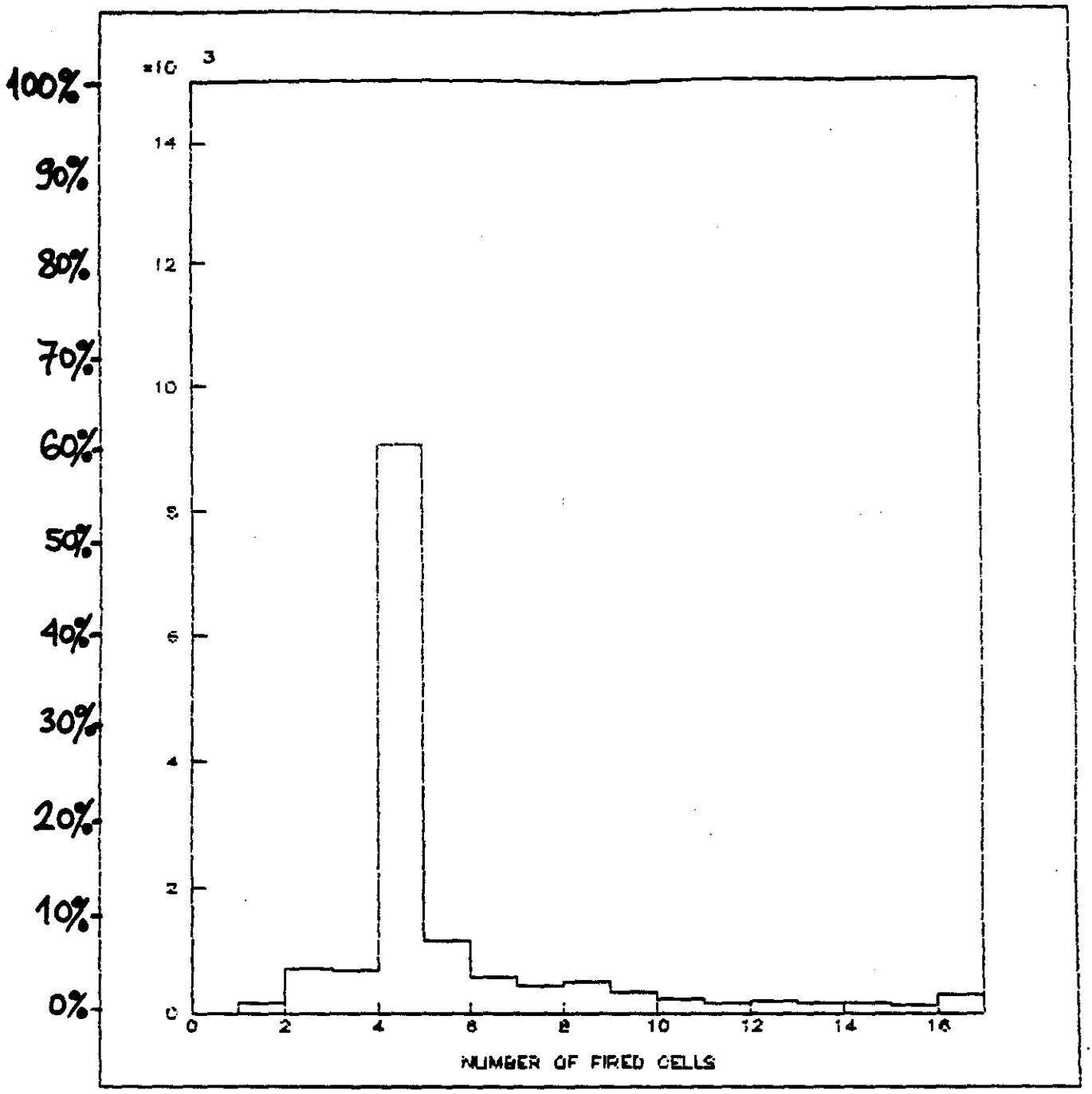
RUN-D012.DAT $Ar + C_4H_{10} = 1+3$ (SQS) Threshold = 15 mV

~ 0.5 TeV muons



RUN - D012. DAT

$Ar + C_4H_{10} = 1+3$
SQS mode
0.5 TeV MUONS



RUN-D013.DAT

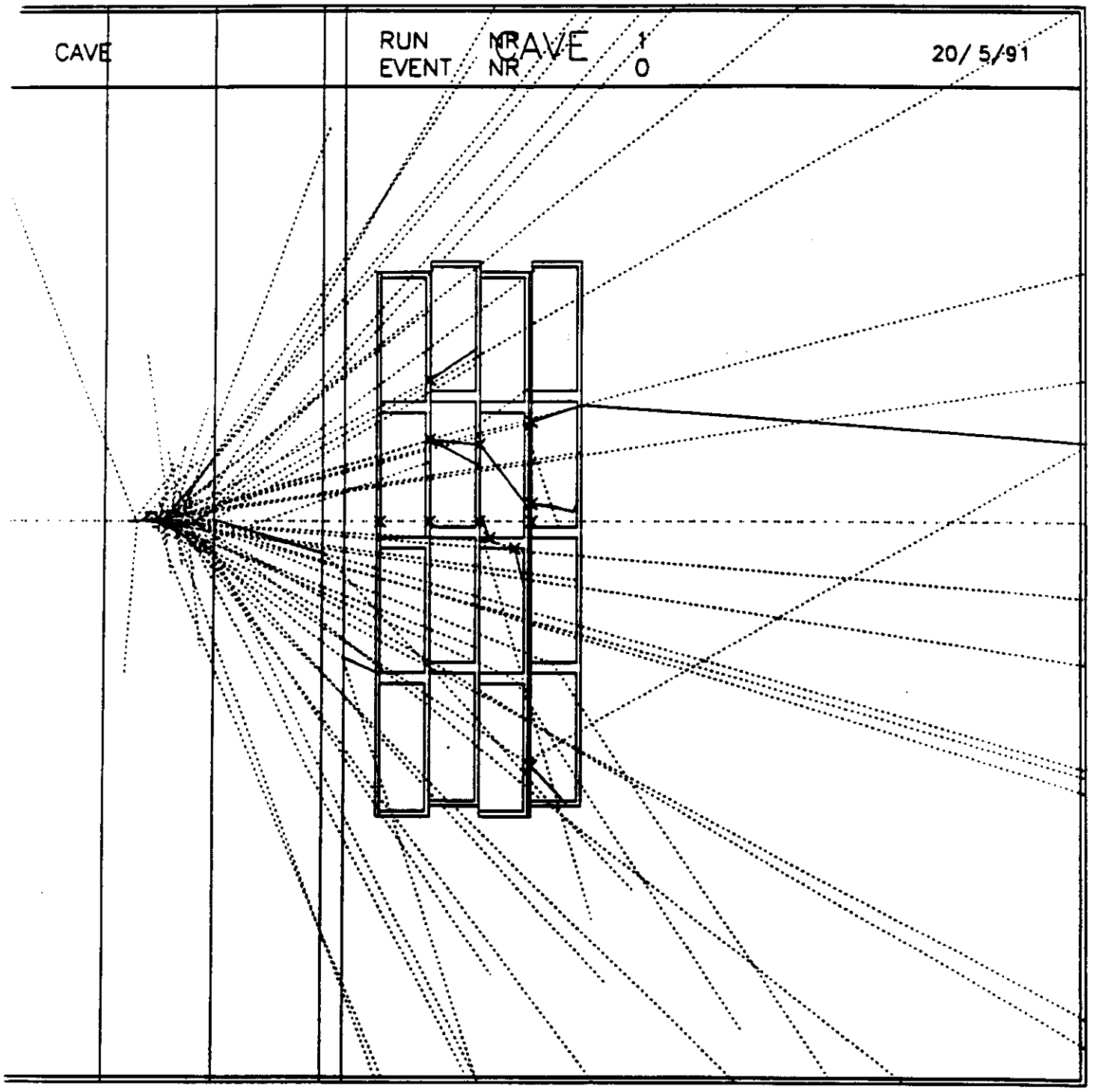
10 cm LEAD in front

$Ar + C_4H_{10} = 1+3$

SQS mode

0.5 TeV MUONS

Example from
Yu. Gornushkin's simulation

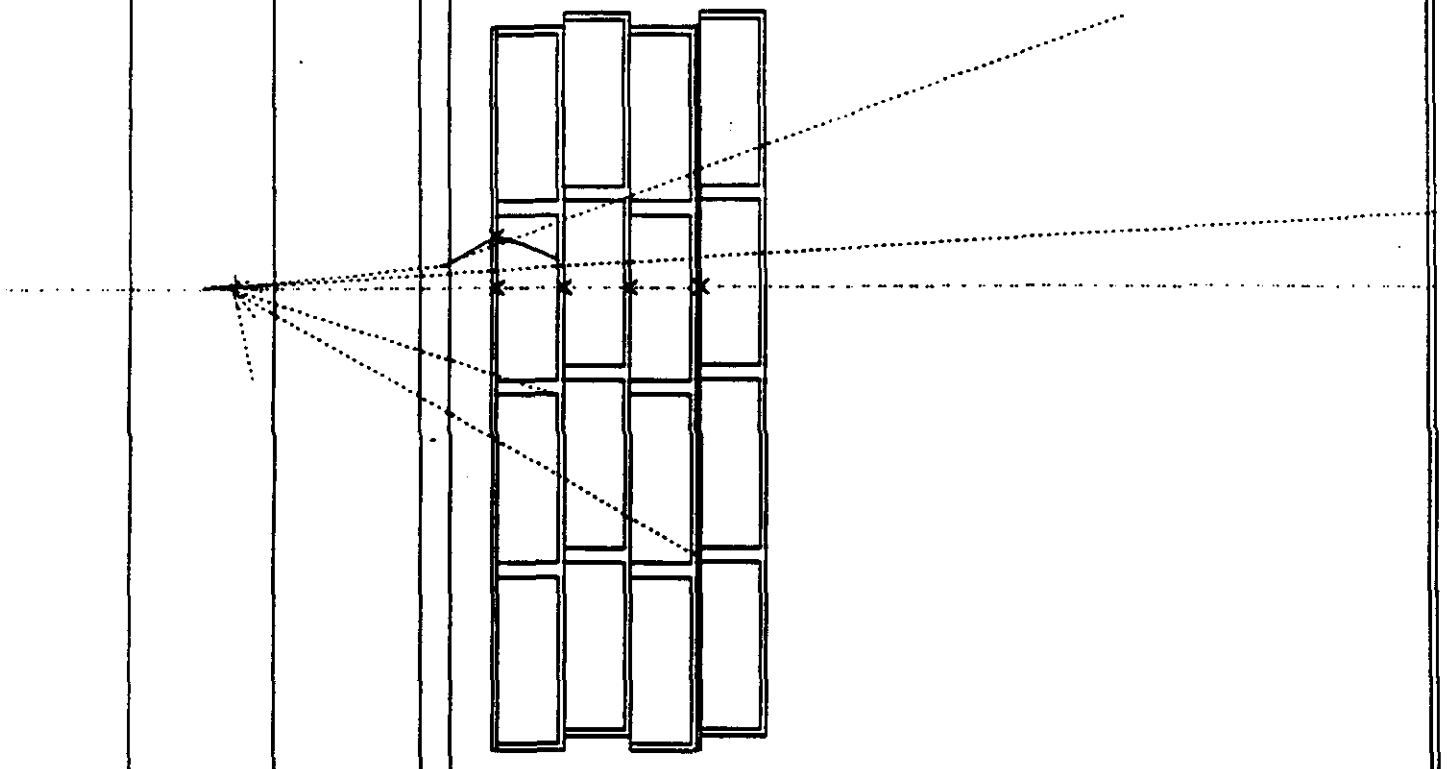


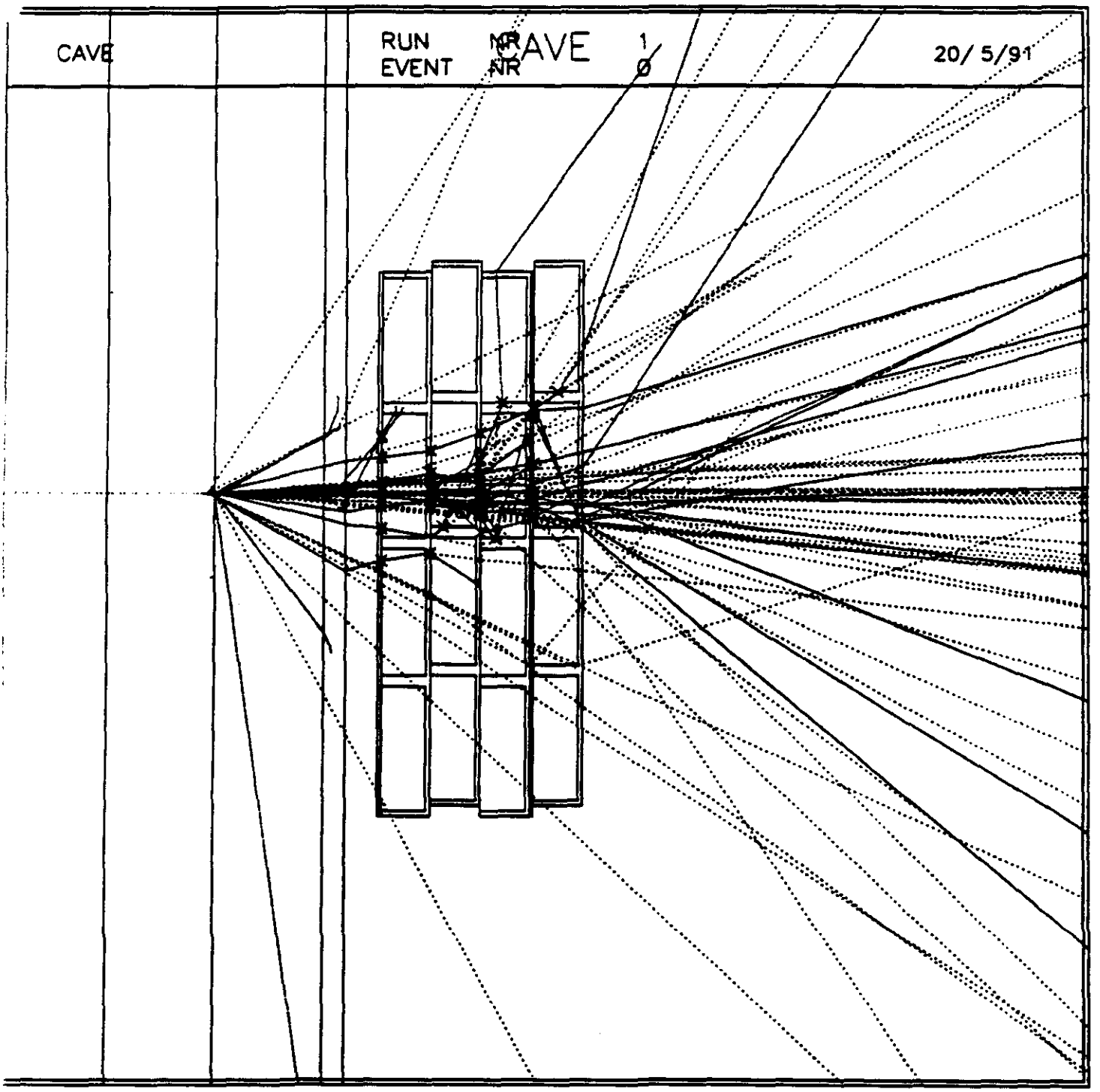
CAVE

RUN NR 1
EVENT NR 0

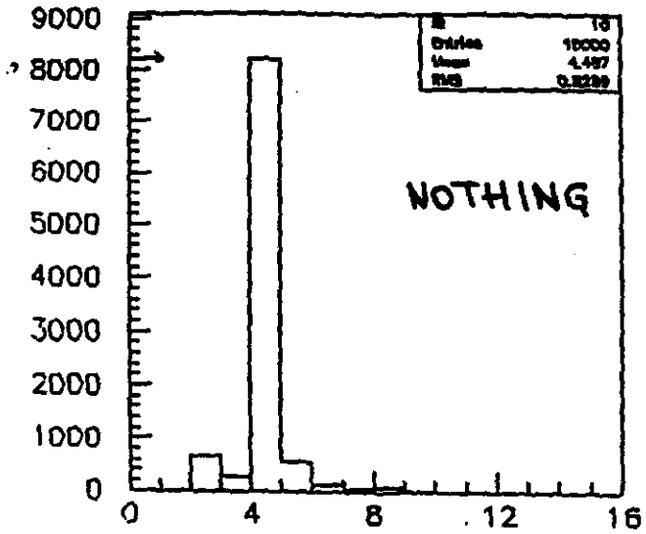
CAVE

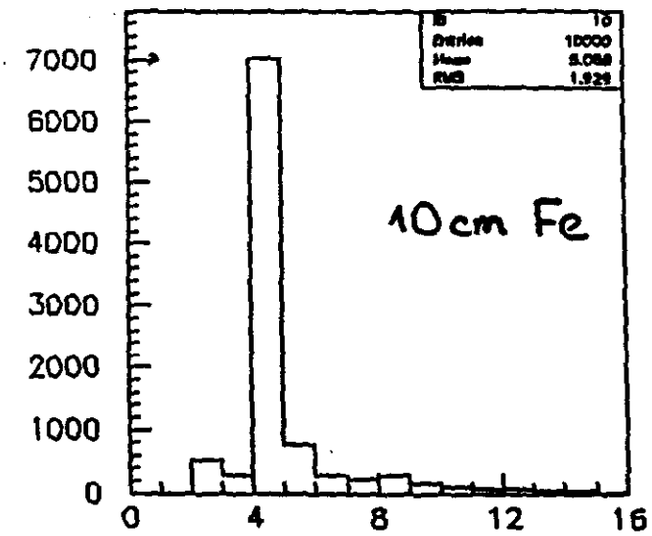
20/ 5/91

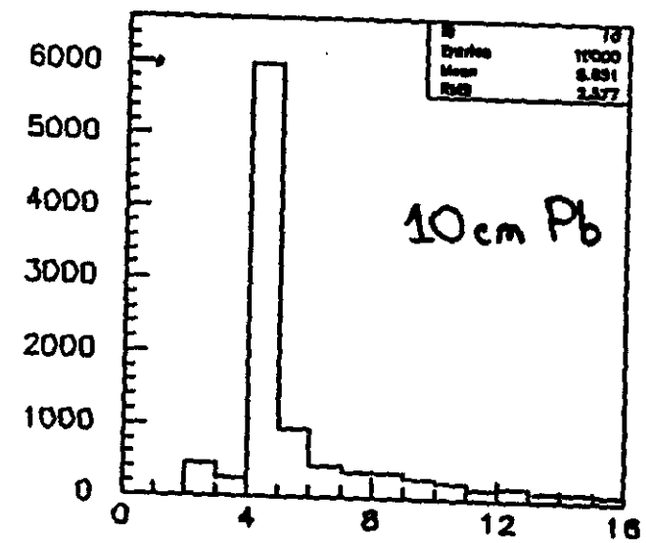



CAVE
RUN NR
EVENT NR
CRAVE
1
Ø
20/ 5/91

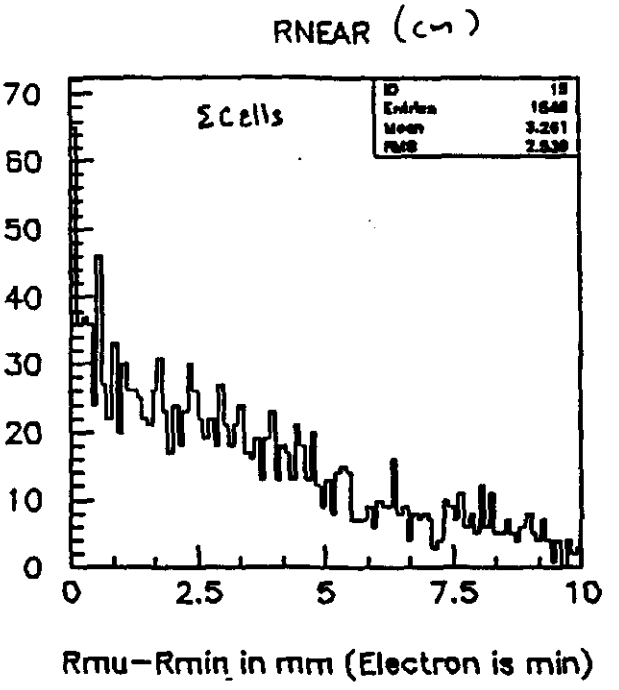
STAR1 of SIMULATION by R. McNeil



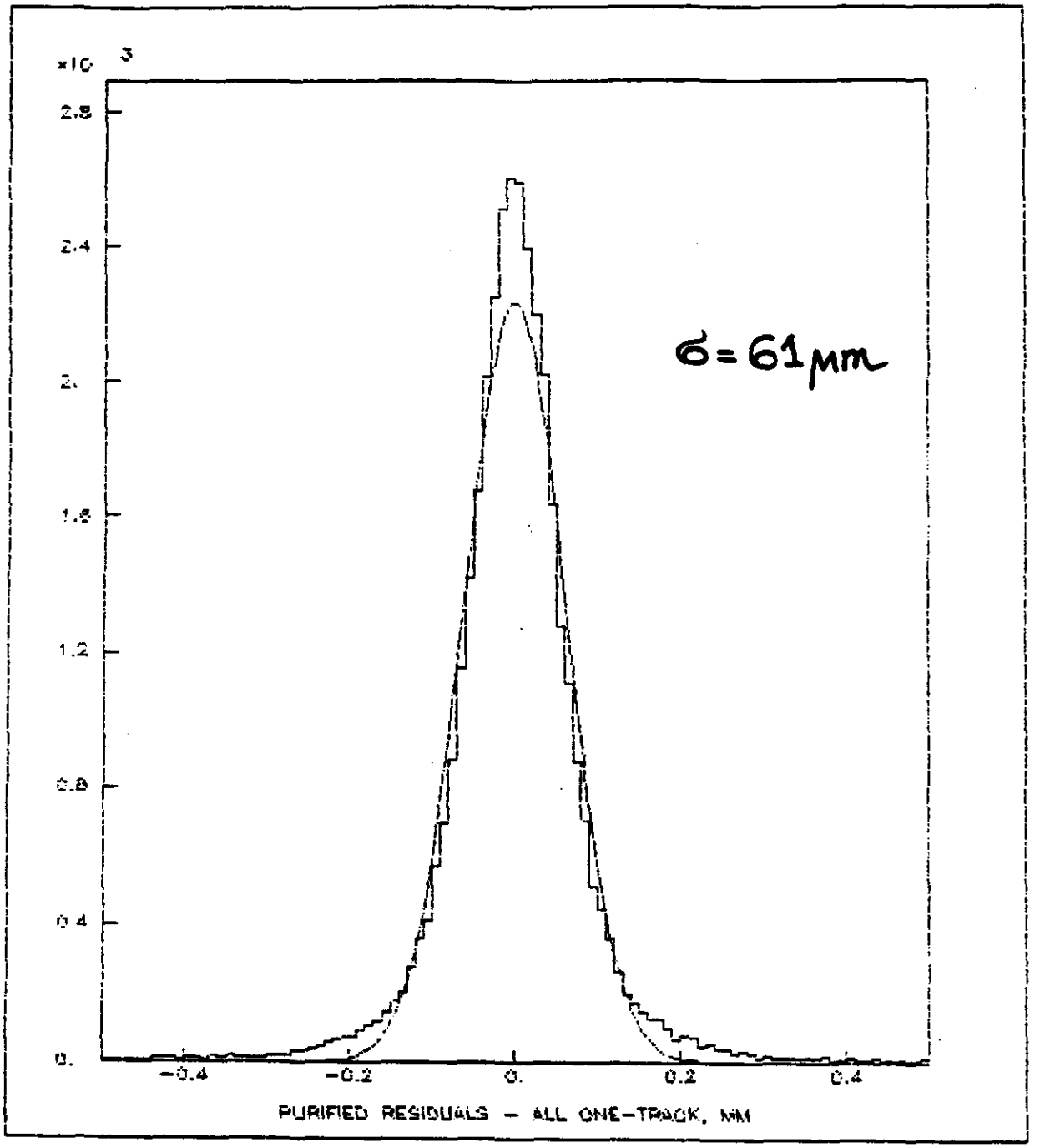




NUMBER OF CELLS WITH HITS



$r_0 - r_{meas}$ distribution



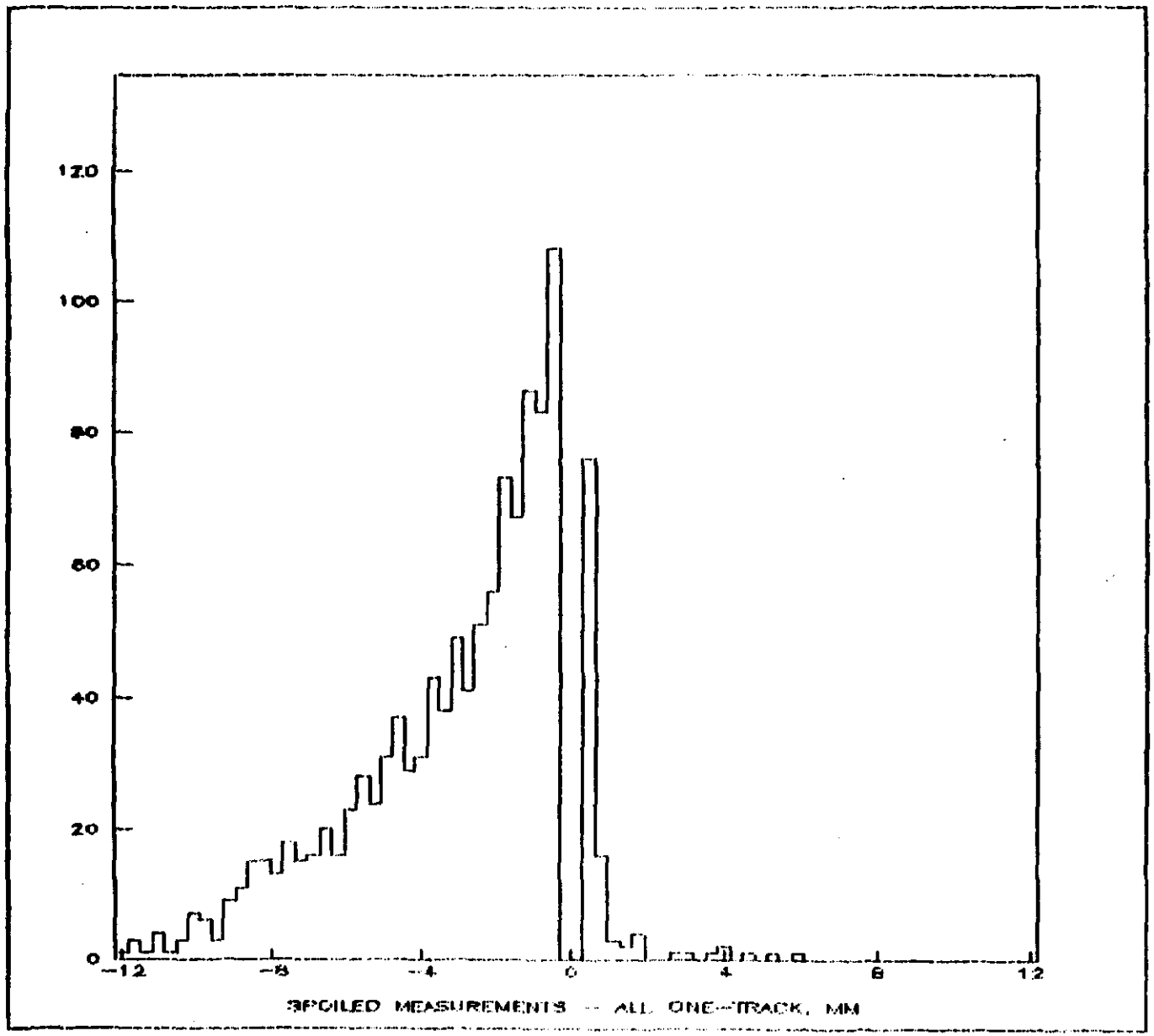
RUN-D013.DAT

10 cm LEAD in front

$Ar + C_4H_{10} = 1+3$

SQS mode

0.5 TeV MUONS



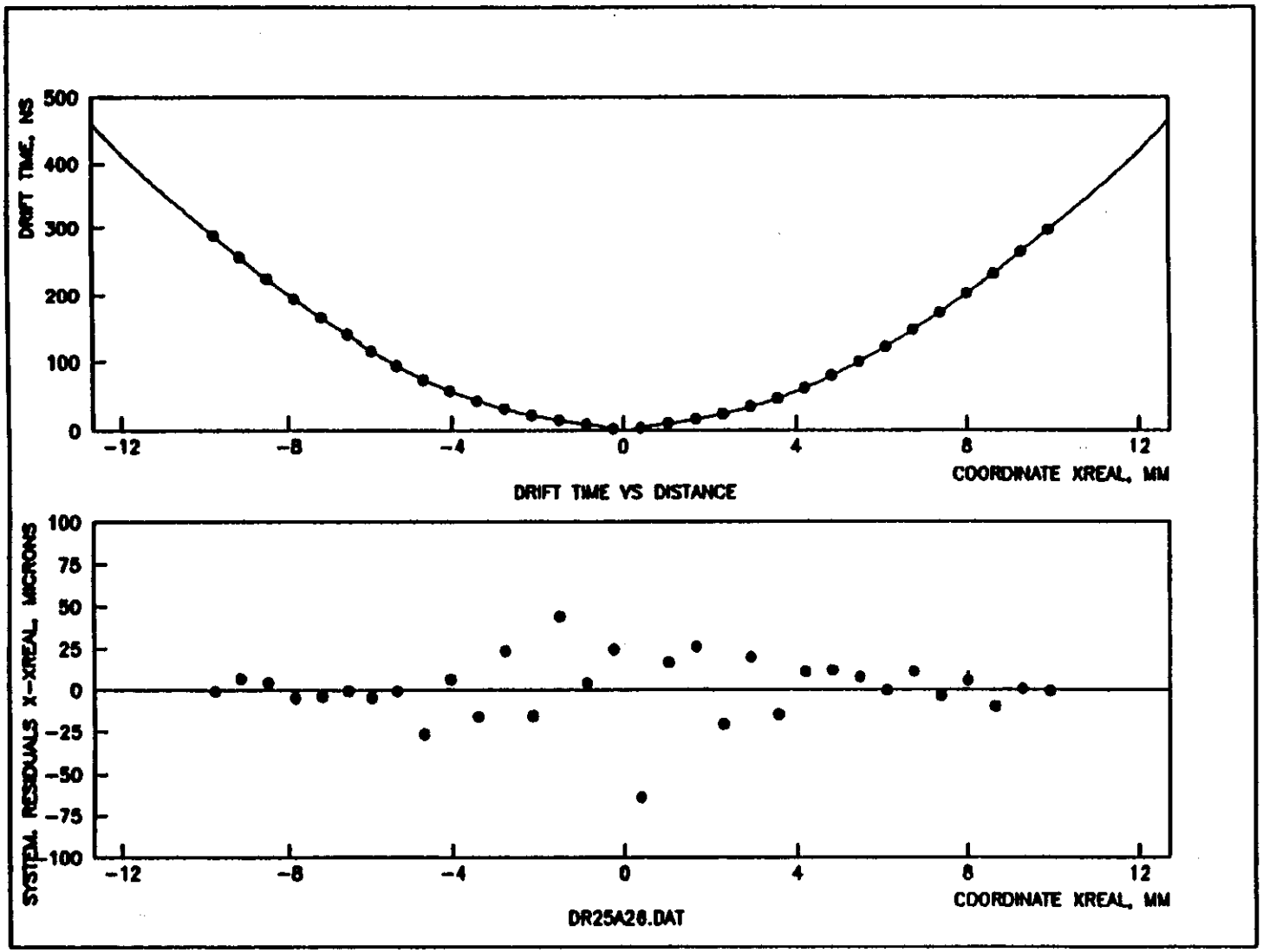
RUN - D013. DAT

10 cm LEAD in front

SOME FIGURES from PRELIMINARY ANALYSIS

	-D012.DAT (NOTHING)	-D014.DAT (10cm Fe)	-D013.DA (10cm Pl
"4-CELL" EVENTS	75% (82)	65% (70)	61% (60
"ONE-TRACK" EVENTS	92.4	87.7	87.4
"TWO-TRACK" EV.	4.2	7.0	7.4
"THREE-TRACK" EV.	1.4	2.1	2.8
"FOUR-TRACK" EV.	2.0	3.1	2.4
(corected on geometry non-efficiency)			
PURIFIED	17.5%	22.2%	23.5%
FAILED TO FIND A TRACK	3.4%	4.6%	5.3%
ONLY ONE SPOILED MEAS.	10.0	11.1	12.2
σ_{FIT}	57 μm	–	61 μm
DEV > 4×60 μm	5.4% /cell	7.1%	7.7%
DETECTOR EFFICIENCY	99.3±.2%	99.3±.2%	99.3±.

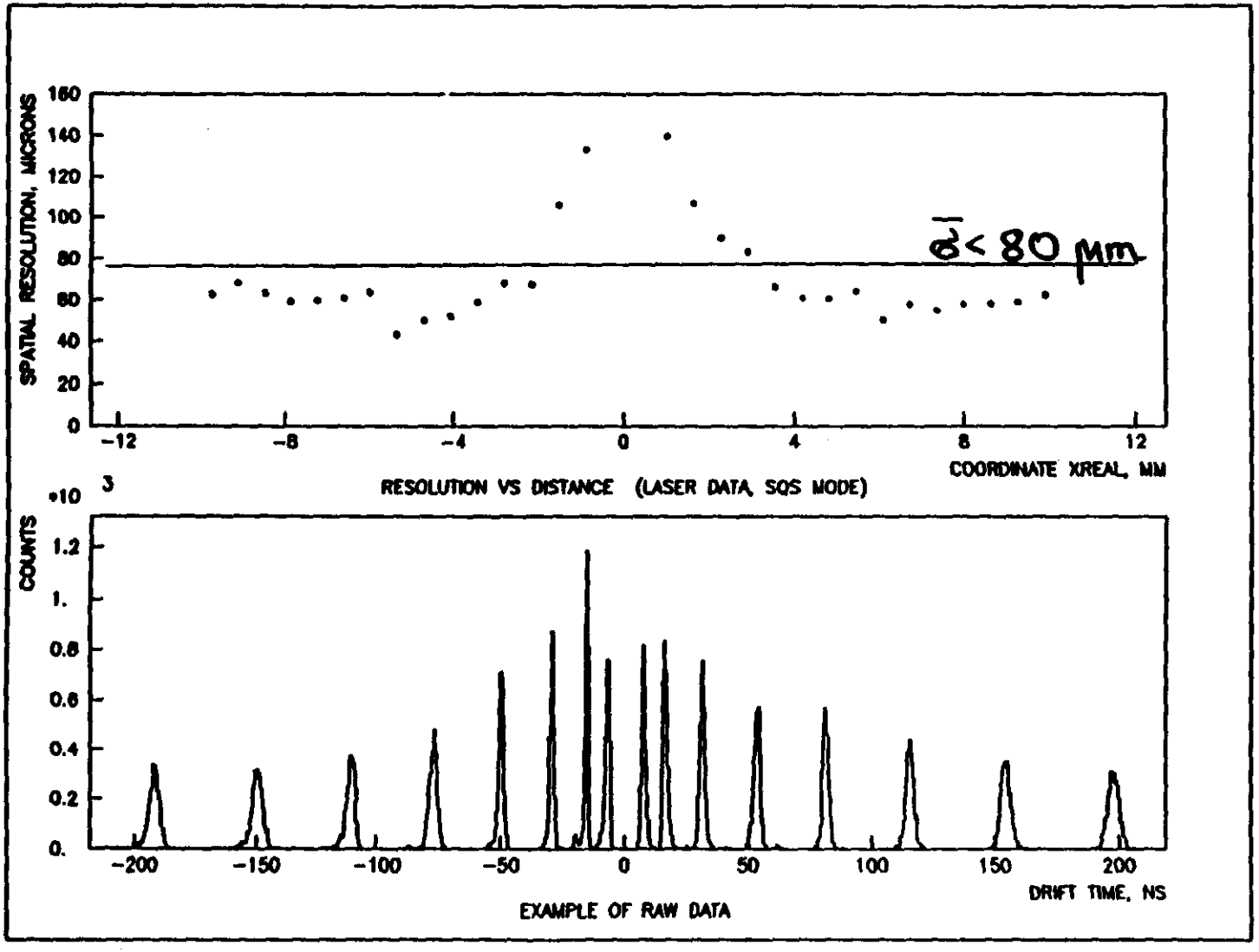
$CF_4 + CO_2 + C_4H_{10} = 40 + 50 + 10$
SQS mode
LASER DATA

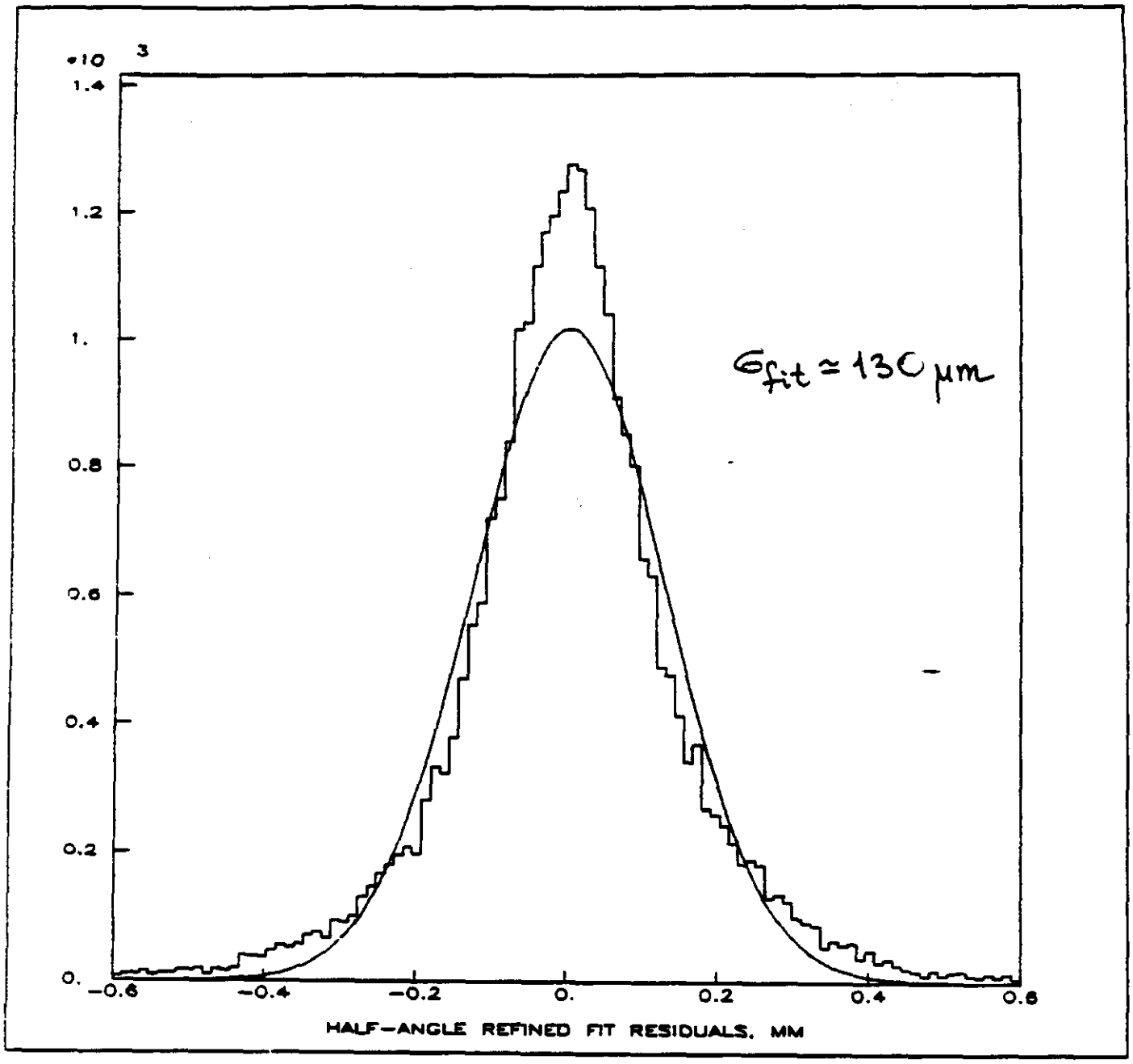


$CF_4 + CO_2 + C_4H_{10} = 40+50+10$

SQS mode

LASER DATA



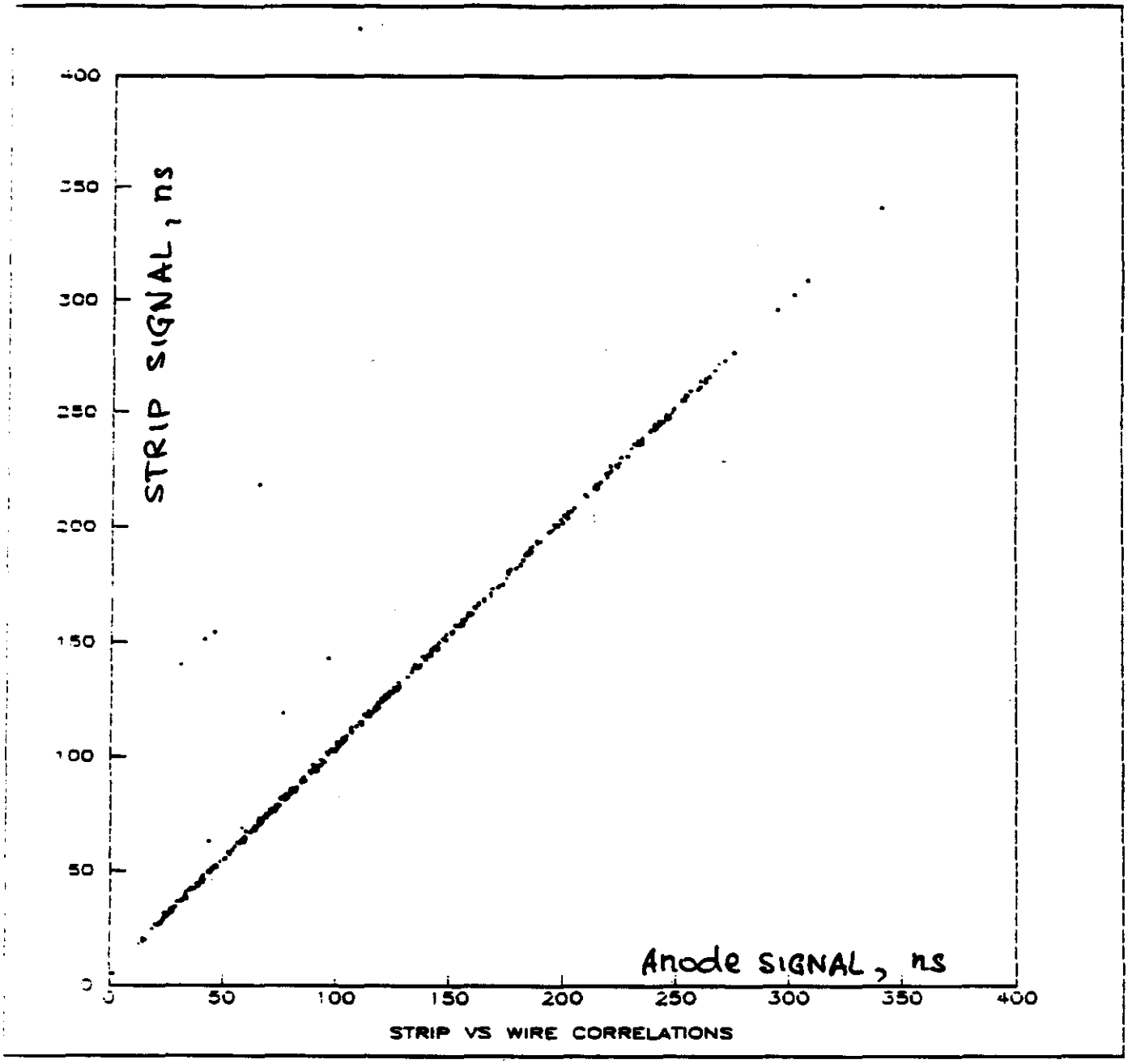


$C_4H_{10} + CO_2 + CF_4 = 10 + 40 + 50$

SQS mode

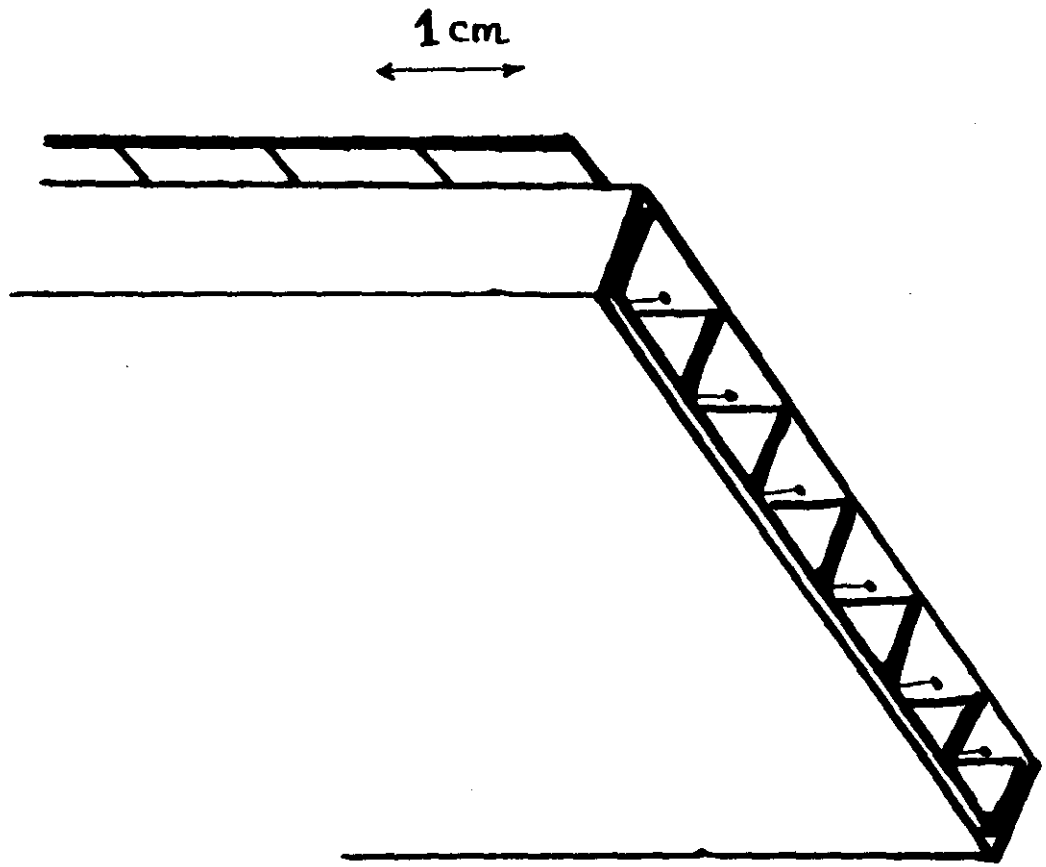
cosmic rays data $\sigma_{fit} = 130\ \mu m$

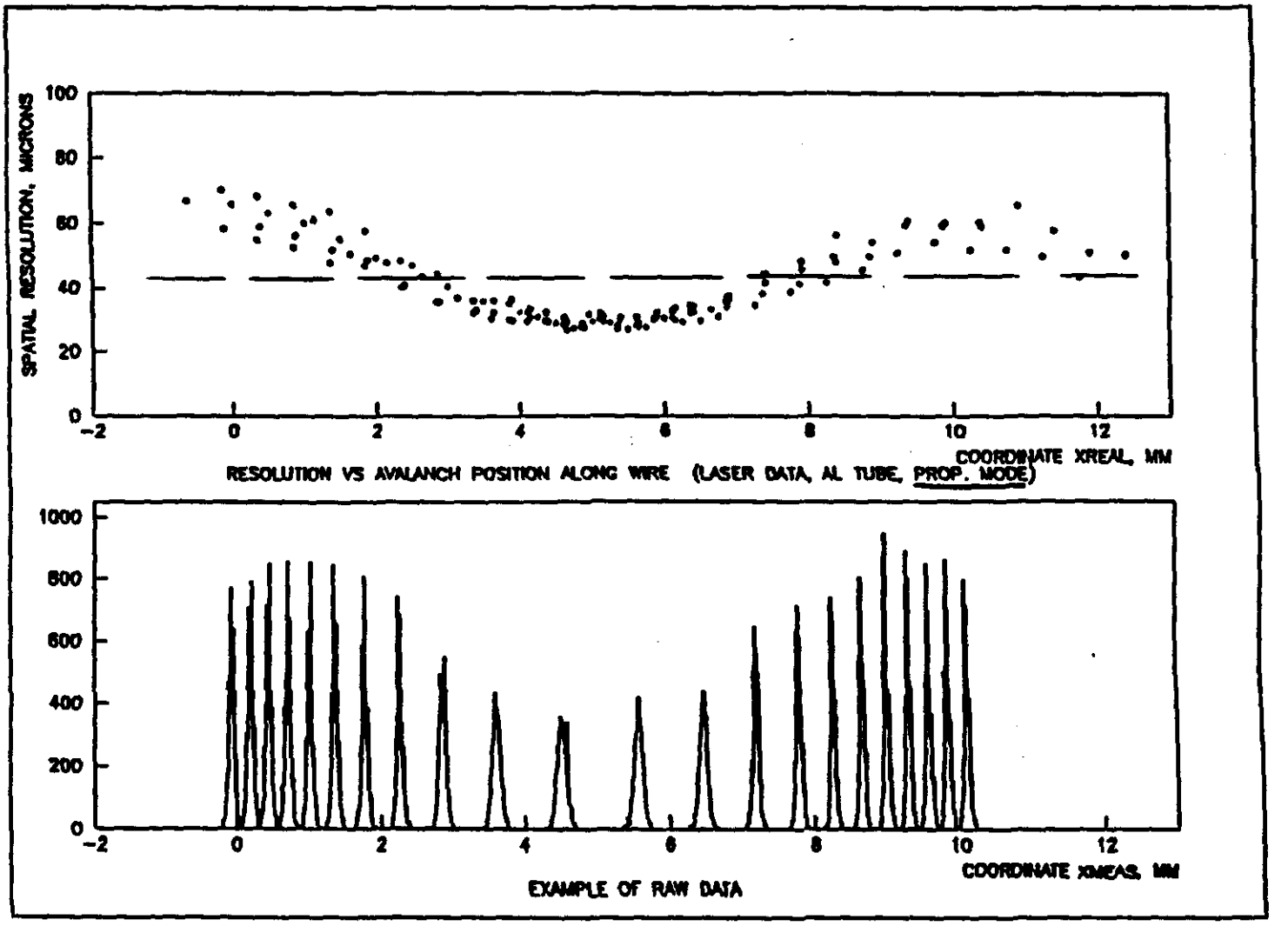
(LASER DATA $\bar{\sigma} \sim 80\ \mu m$)



COSMIC RAYS DATA

$Ar + C_4H_{10} = 1 + 3$ SQS mode

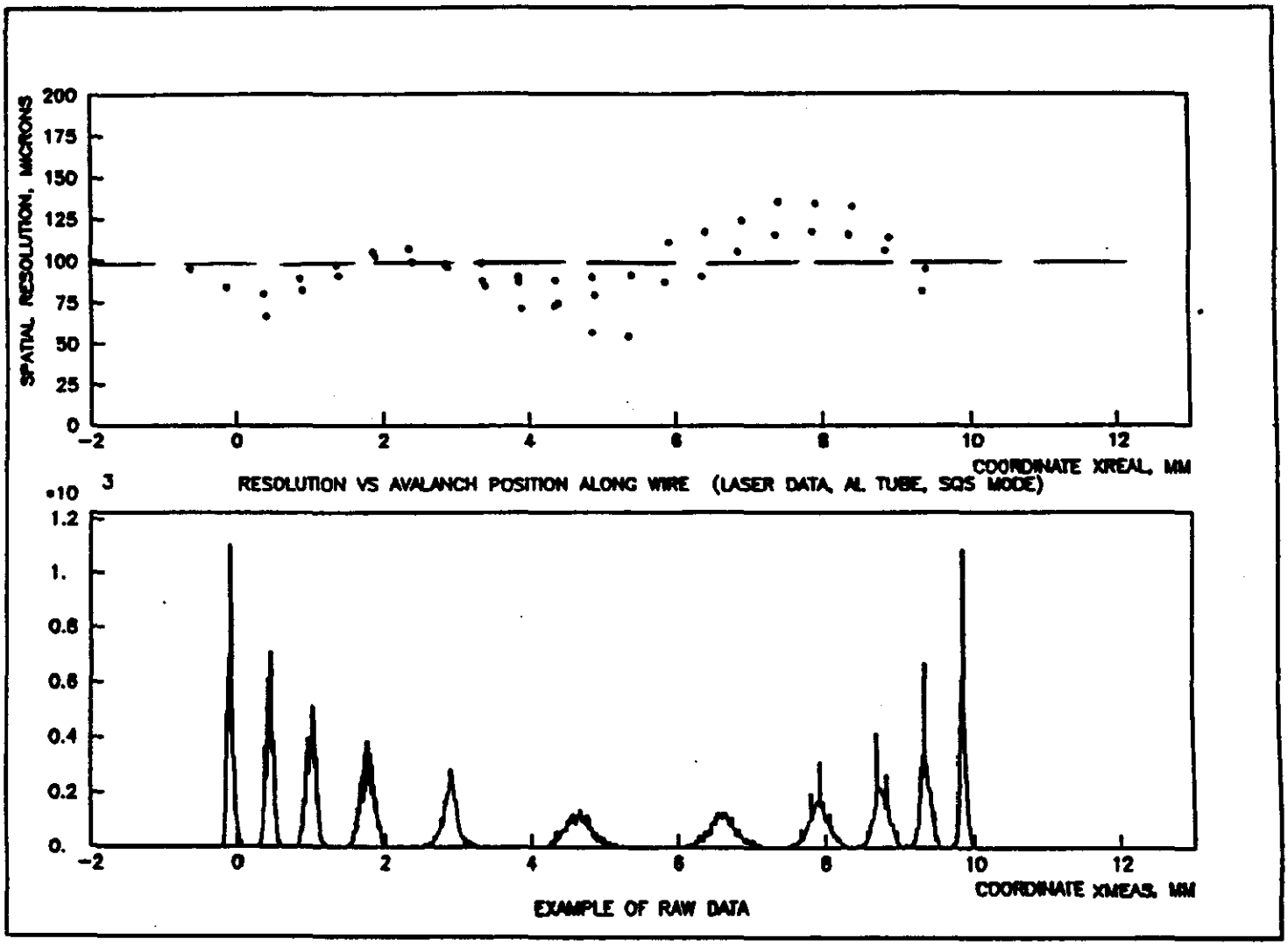

1 cm



STRIP READOUT (LASER, PROP. MODE)

$\langle \sigma \rangle = 41\ \mu m$

Example: points are spaced 500 μm apart



STRIP READOUT (LASER, SQS MODE)

$\langle \sigma \rangle \simeq 95\ \mu m$

Example: points are spaced 1 mm apart

Talk by Roger McNeil

on High Field Option

An Alternate Approach to Muon Detection in GEM

(High Field Option)

M. Atiya and T. Kycia
Brookhaven National Laboratory, Upton, LI, NY 11973

Winston Ko and R. Lander
University of California at Davis, Davis, CA 95616

Q. Fan, G. Fanourakis, T. Ferbel, S. Kanda, S. Olsen, K. Ueno and M. Zielinski
University of Rochester, Rochester, NY 14627

S.K. Kim and S. Schnetzer
Rutgers University, New Brunswick, NJ 08903

R.R. McNeil
Louisiana State University, Baton Rouge, LA 70803

+ others

"10^{34}" EOI

Outline

I. Introduction - Overview

II. Momentum Measurement - Resolution

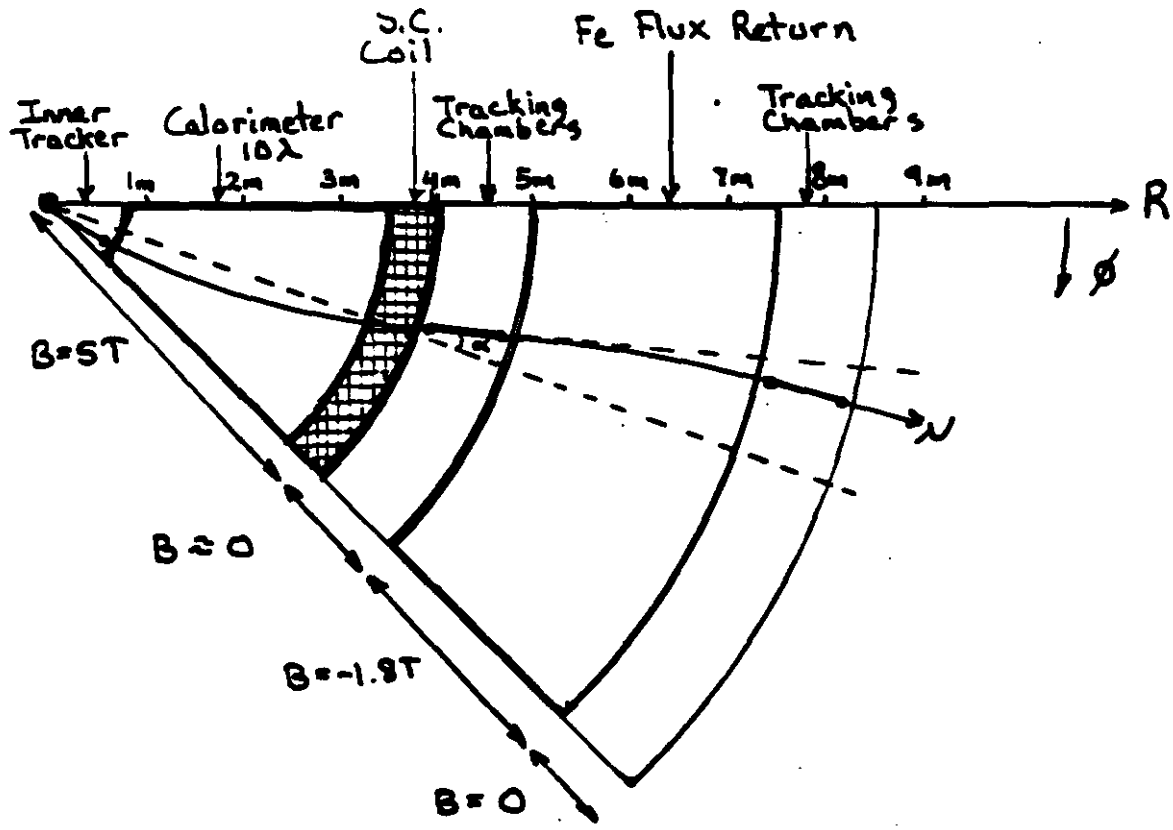
III. Background Simulations

IV. Cost Estimate

V. Summary and Future Work

I. Introduction - Overview

Principle: The point-line measurement has greater sensitivity to momentum than does sagitta measurement



$$\alpha = \frac{0.3\,BR}{2\,P_T} \qquad \text{for } R = 3.6\text{m} \quad B = 5\text{T} \qquad \alpha = \frac{2.7\,\text{mrad}}{P_T\,(\text{TeV}/c)}$$

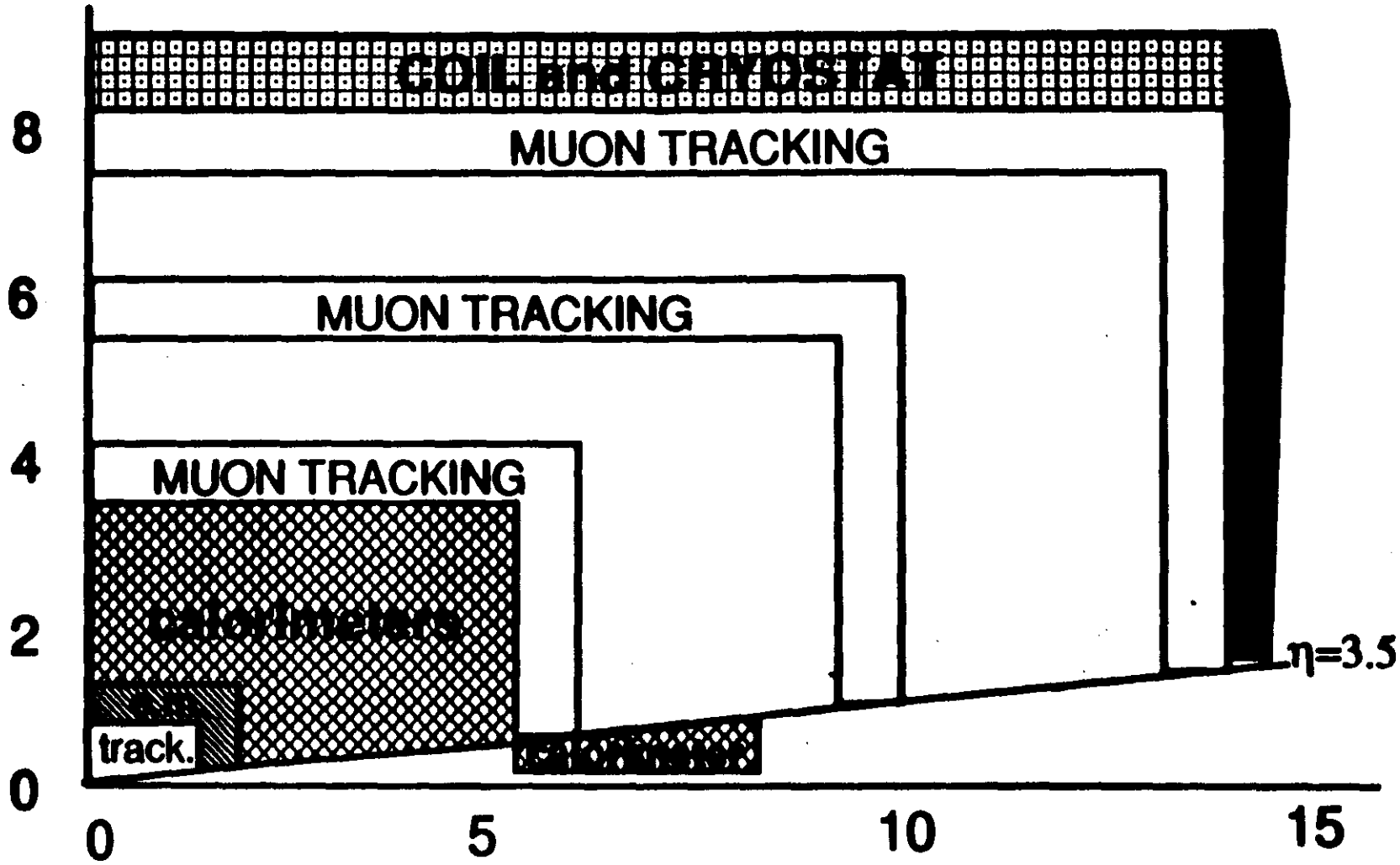
Robust system:

- Redundant measurements of track parameters in inner tracker
- correlations with position/angle of track exiting iron yoke

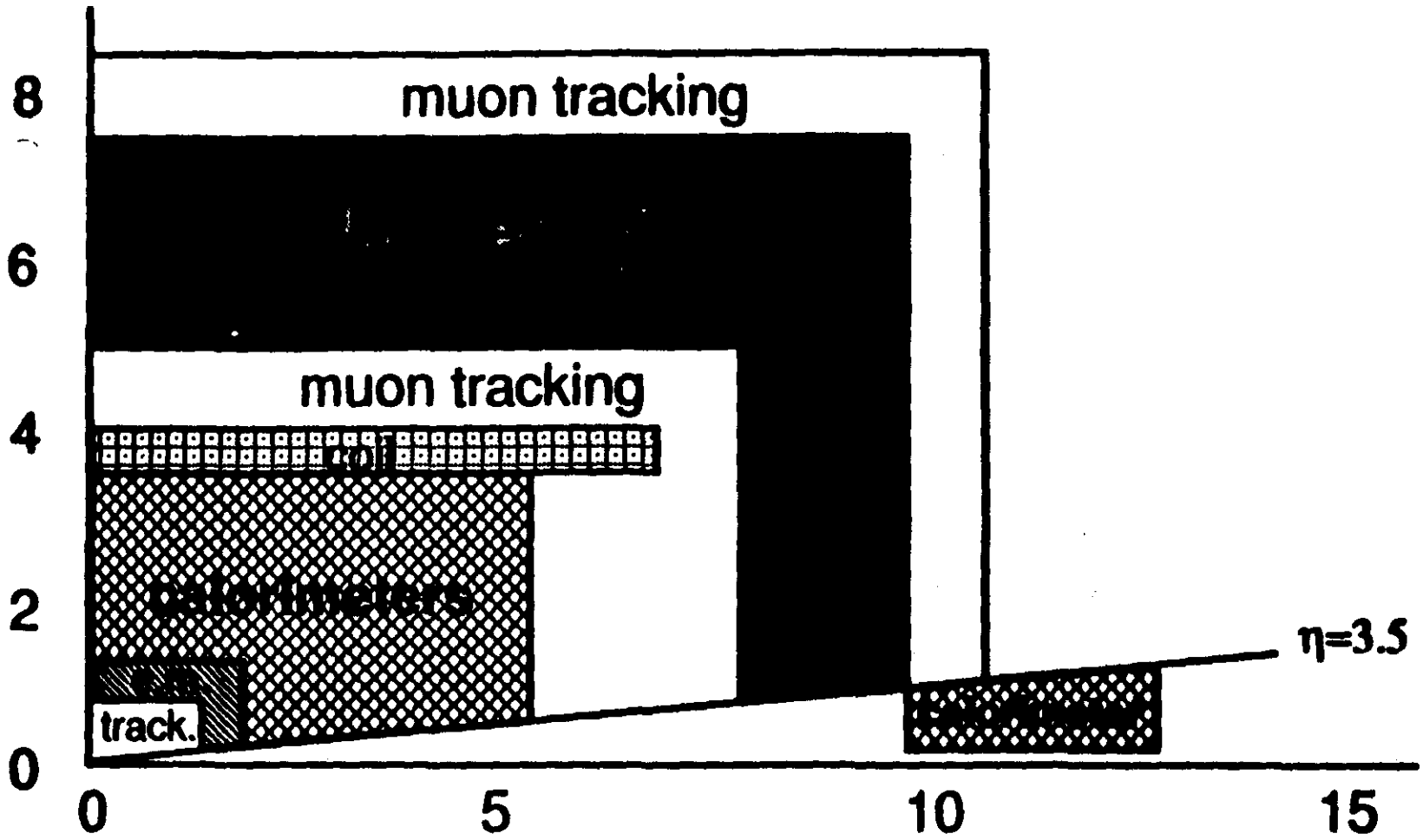
Simple Trigger: Radial Track outside flux return (ν ID)

*

Radial Track inside flux return (P_T cut)



Baseline Design of GEM



High Field Design for GEM

- Inner Detector Geometry unchanged
- Inner Tracker now at B = 5T

II. Momentum Measurement - Resolution

Point (vertex) - Slope (α) Measurement

$$\alpha = \frac{2.7\,\text{mrad}}{P_T(\text{TeV}/c)}$$

$$\theta_{ms} = \frac{0.014}{P_T(\text{GeV}/c)} \sqrt{\frac{X}{X_0}}$$ where X is # radiation lengths

《 Want low-Z Calorimeter 》

Recommend Hadronic Calorimeter with Stainless Steel Radiator

Then,

$$X \simeq \underset{\text{EM}}{30X_0} + \underset{\text{Had}}{\sim 80X_0} + \underset{\text{Coil}}{\lesssim 20X_0} = 130\,X_0$$

or

$$\theta_{ms} = \frac{0.16\,\text{mrad}}{P_T(\text{TeV}/c)}$$

need to measure α to $\sim .1$ mrad @ 1 TeV

need to measure exit position to better than $\sim 300\,\mu$m

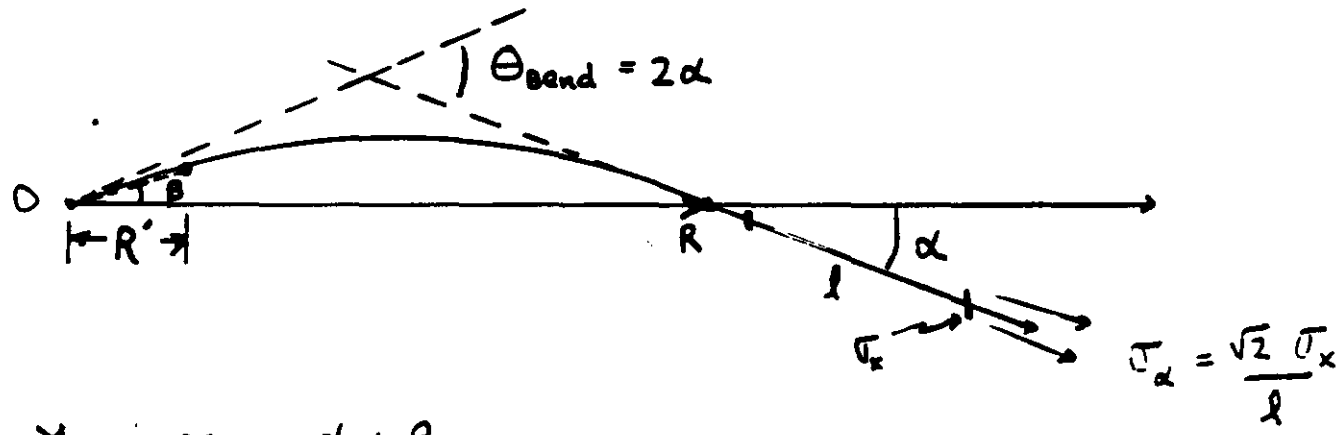
《 Modest μ system requirements 》

Then limiting resolution given by

$$\frac{\Delta P_T}{P_T} = \frac{\theta_{ms}}{\alpha} \simeq 6\%$$

Independent of P_T! Without inner tracker!

The momentum measurement can be improved by using a single position measurement from inner tracker



Measure $\alpha + \beta$

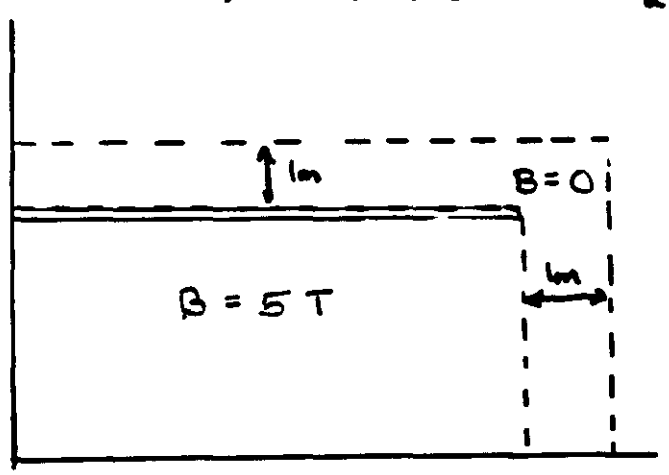
Then
$$\frac{\Delta P_T}{P_T} = \left[\left(\frac{\theta_{ms}}{\alpha+\beta} \right)^2 + \left(\frac{\sqrt{\sigma_\alpha^2 + \sigma_\beta^2}}{\alpha+\beta} \right)^2 \right]^{1/2}$$

independent of P_T — depends on P_T

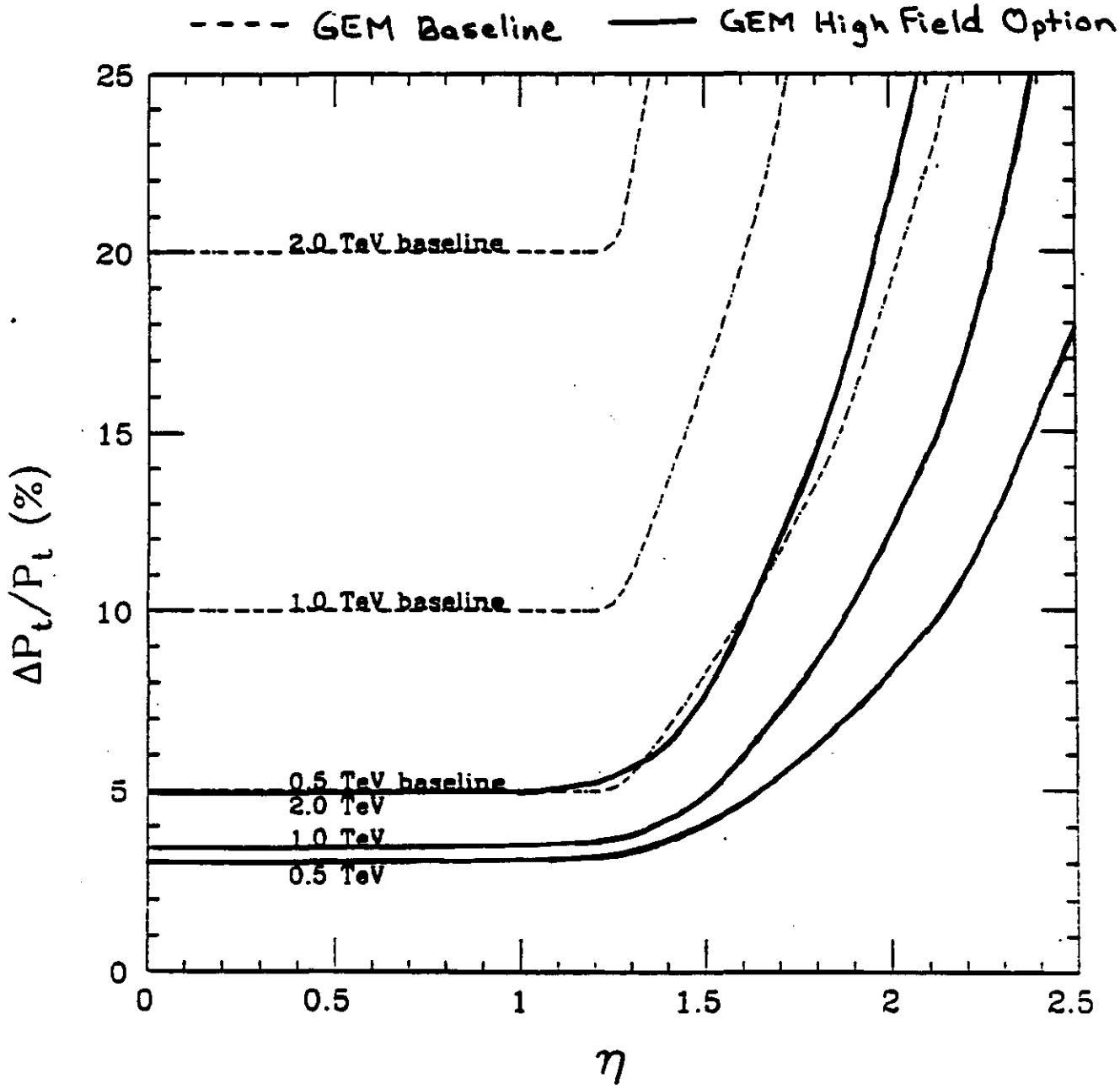
Parameters used: (R. Lander)

$R' = 0.75\,m$, $R = 3.7\,m$ $\quad l = 1\,m$ $\quad \sigma_x = 50\,\mu m$

$X = 110\,X_0$ $\quad \sigma_\alpha \underset{\text{assume}}{=} \sigma_\beta = \cancel{0.5}\,mrad$ 0.07



Comparison of Resolution curves
GEM Baseline vs High Field Option ($\alpha + \beta$ measured)



If no inner tracker - High Field Curves shift up by factor ~2

If Pb-based hadron Cal - High field curves shift up by factor ~1.6

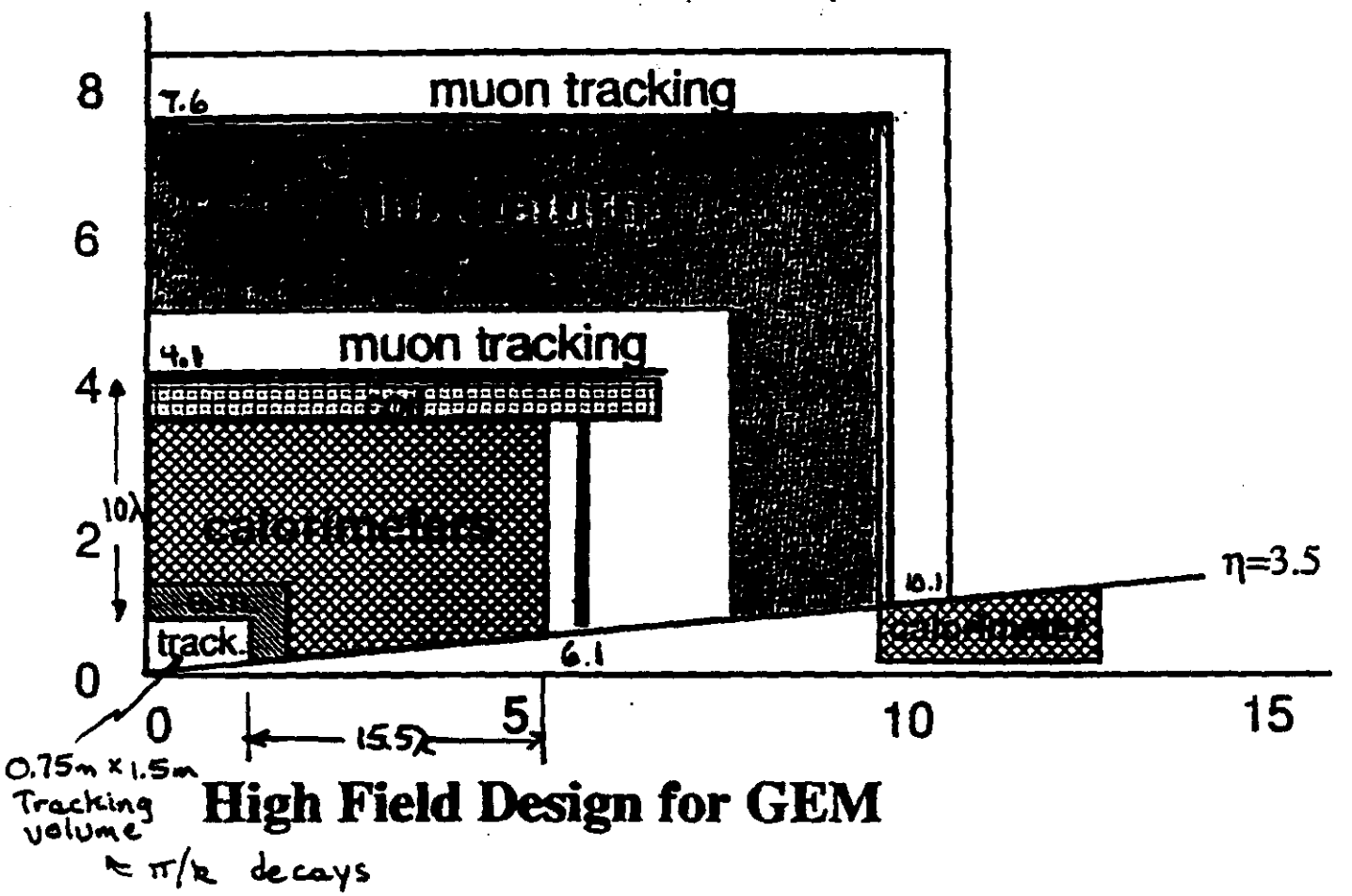
III. Background Simulations

Simulation of chamber/trigger rates

USED ISAJET TWOJET events $P_T^{JET} > 5\,GeV/c$

Rates calculated for $|\eta| < 2.5$

Used PCHTHR code for punchthrough Simulation
(see transparancies of my July 17th GEM talk at SSCL)

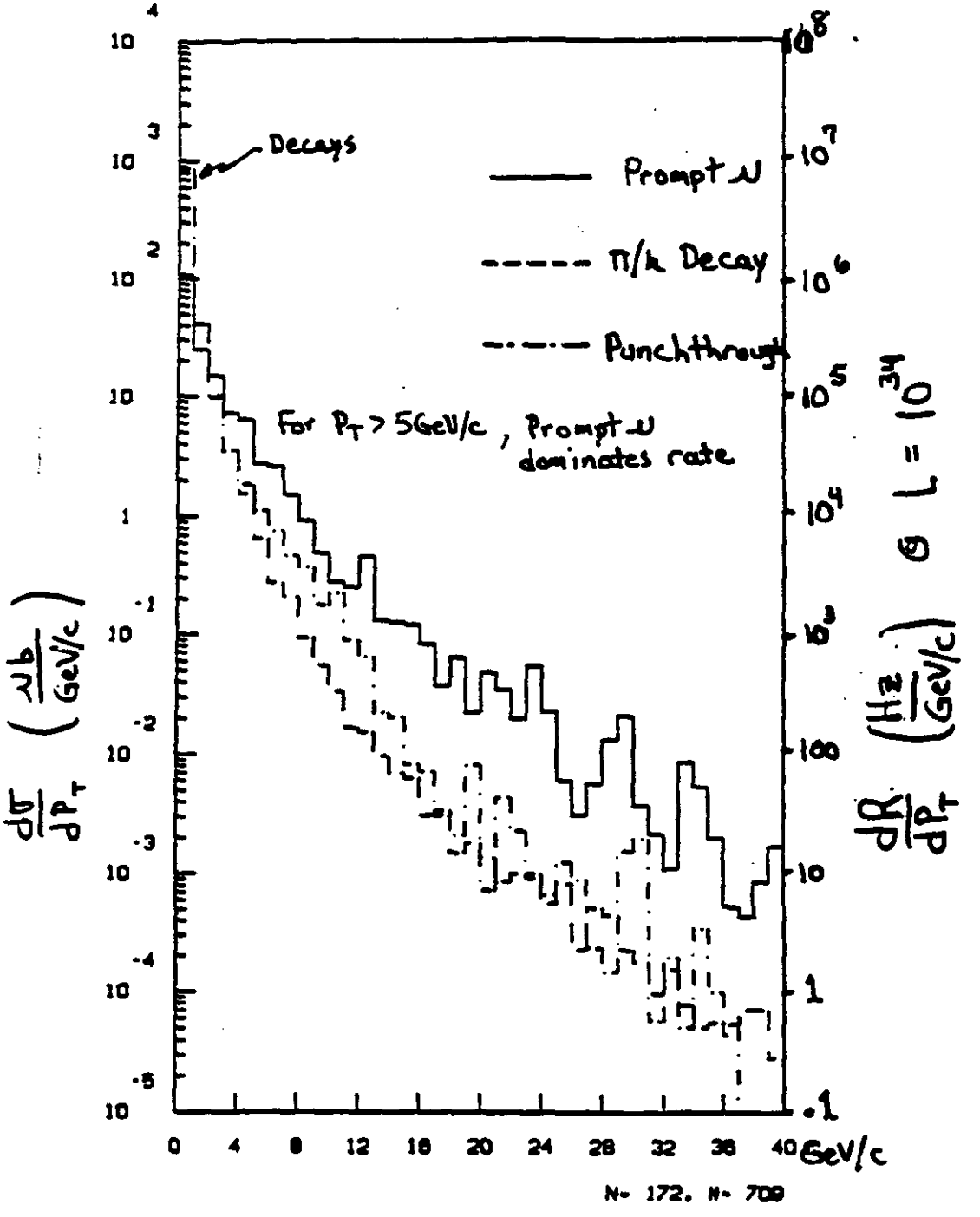


High Field Design for GEM

- No magnetic field yet included
- Everything exiting calorimeter assummed to be a muon

} Conservative

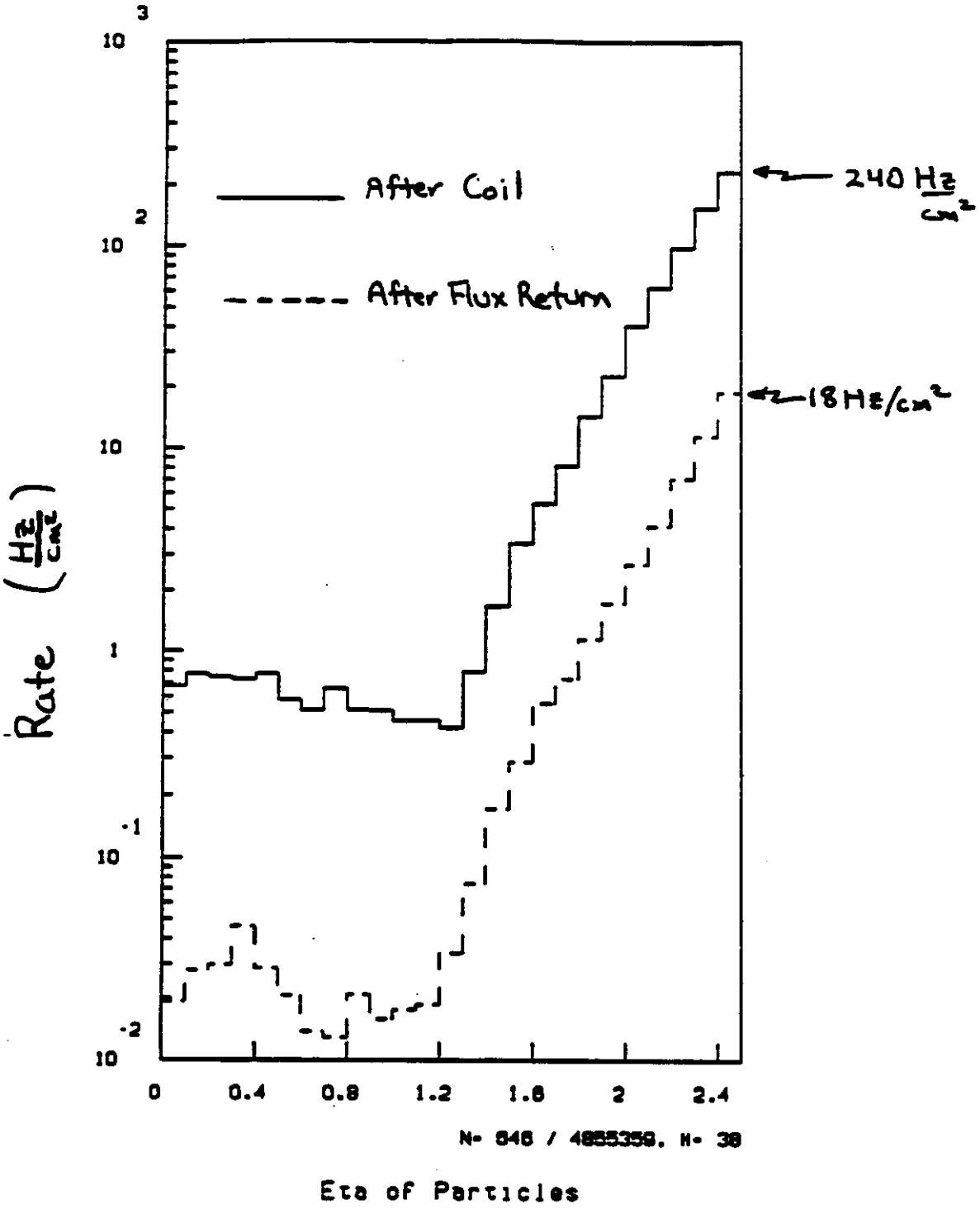
TWØJET EVENTS Pt(JET)>5GeV/c ISAJET Simulation



Pt (GeV/c) after Calorimeter

A $P_T > 10$ GeV/c cut ⇒ 10^4 Hz 1ST Level trigger rate @ 10^{34}

TWØJET EVENTS Pt(JET)>5GeV/c ISAJET Simulation



The High Field in the Calorimeter aids in Punchthrough background suppression

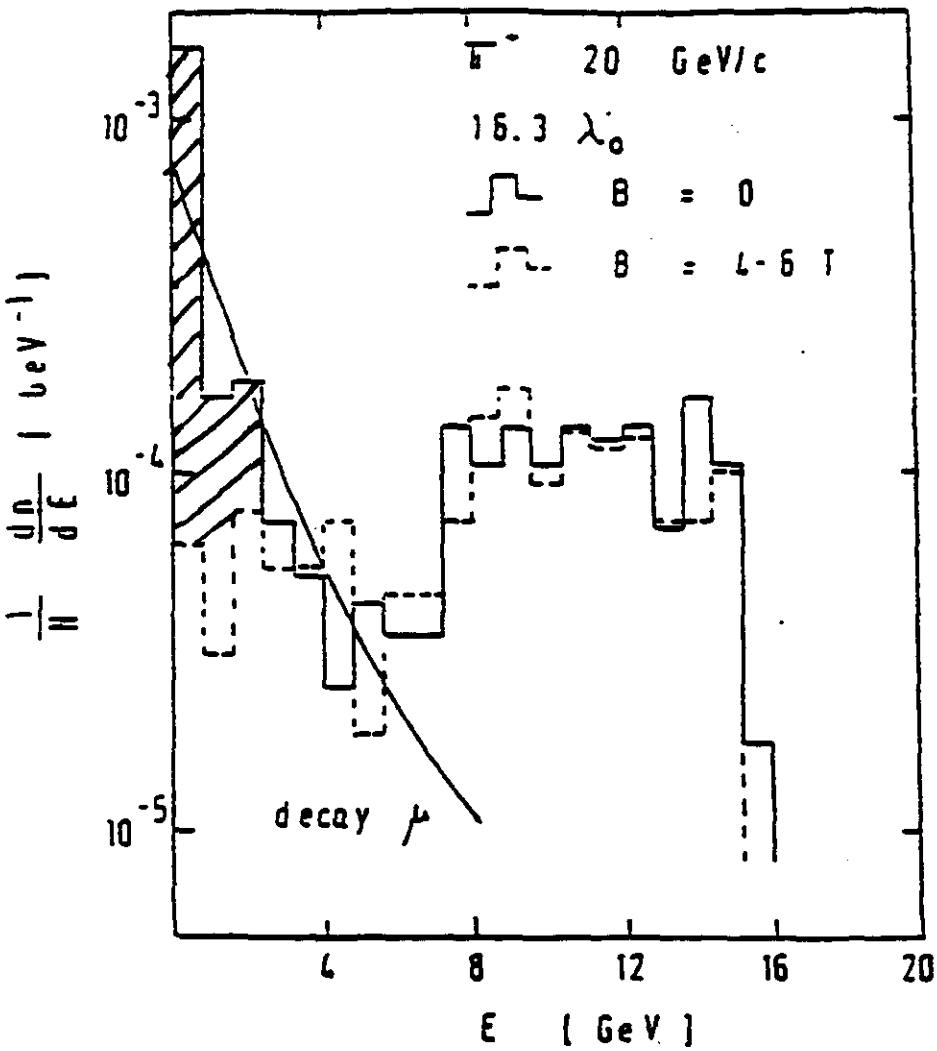


Fig. 3 : Energy spectrum of the decay muons produced by 20 GeV pions after 16.3λ of absorber with magnetic field on (dashed histogram) and off (full histogram). The full line is a parametrization from ref (4).

DRDC proposal P7
presented by M. Della Negra
simulation by H. Fesefeldt

//// ~50 % of punchthrou

Background From Muon-induced showers

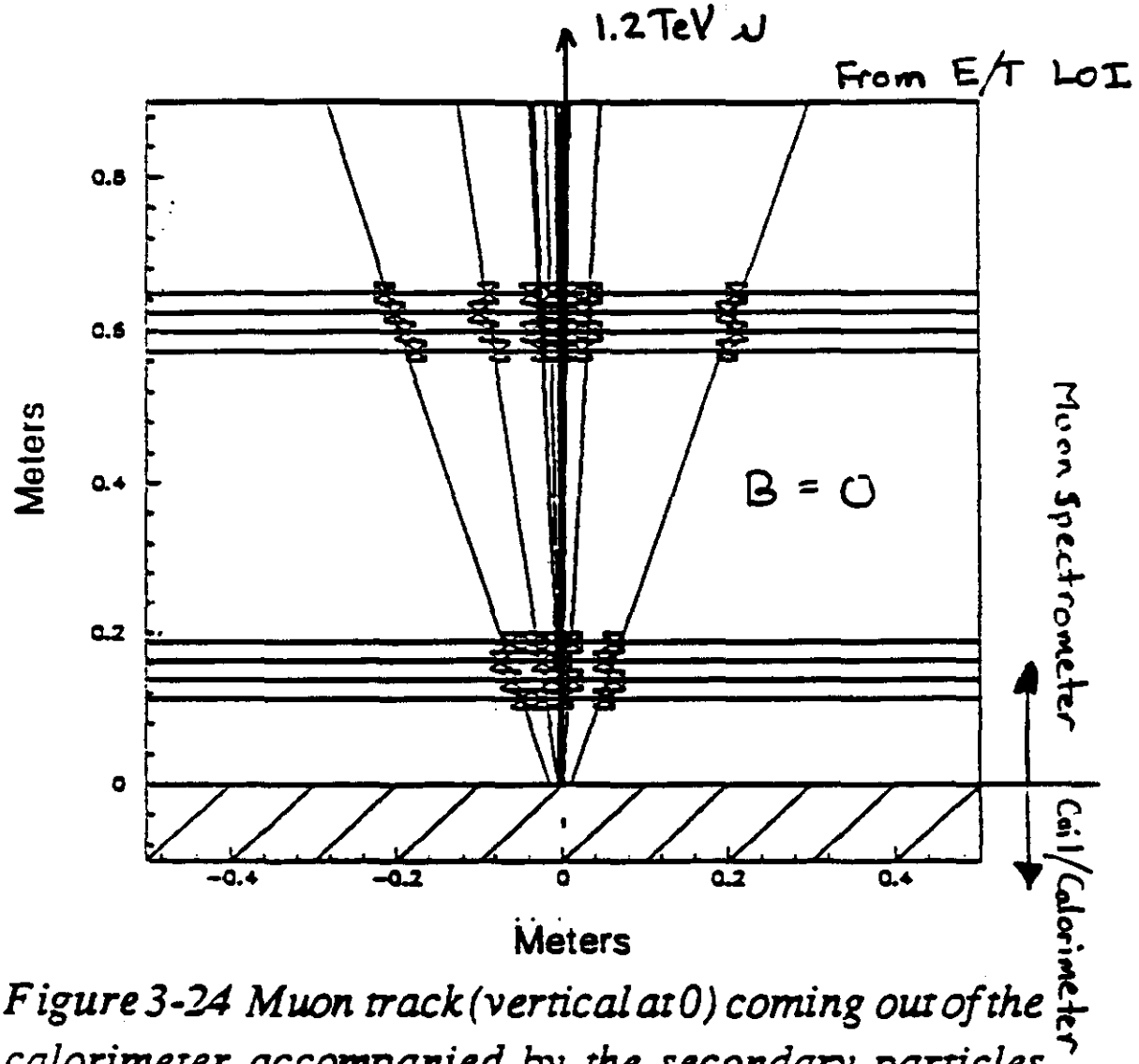


Figure 3-24 Muon track (vertical at 0) coming out of the calorimeter accompanied by the secondary particles resulting from muon radiation in a 4 TeV Z′ event. (Atypical)

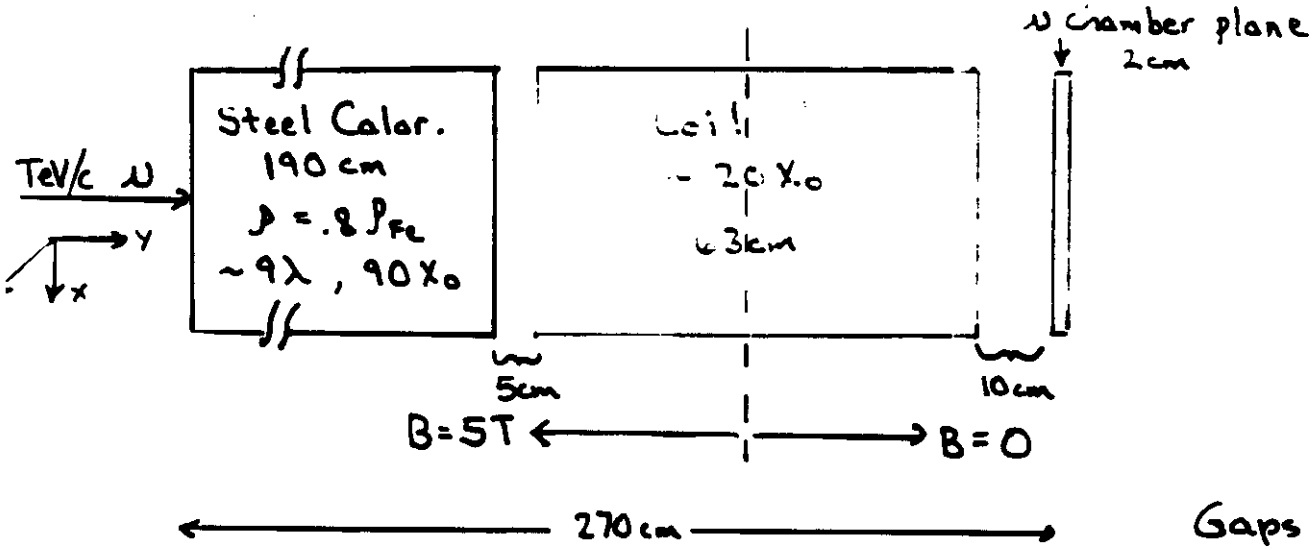
Results of E/T Study: Good hit ≡ no other tracks in cell

Cell Size		All 8 good hits	4 good hits (1 good S.L.)
2.5 cm	4 TeV Z′	75.5 %	85.0 %
	high P_T t	87.6 %	94.0 %
1 cm	4 TeV Z′	82.0 %	92.0 %
	high P_T t	91.7 %	96.8 %

GEANT Simulation of Muon-induced showers for GEM High Field Option

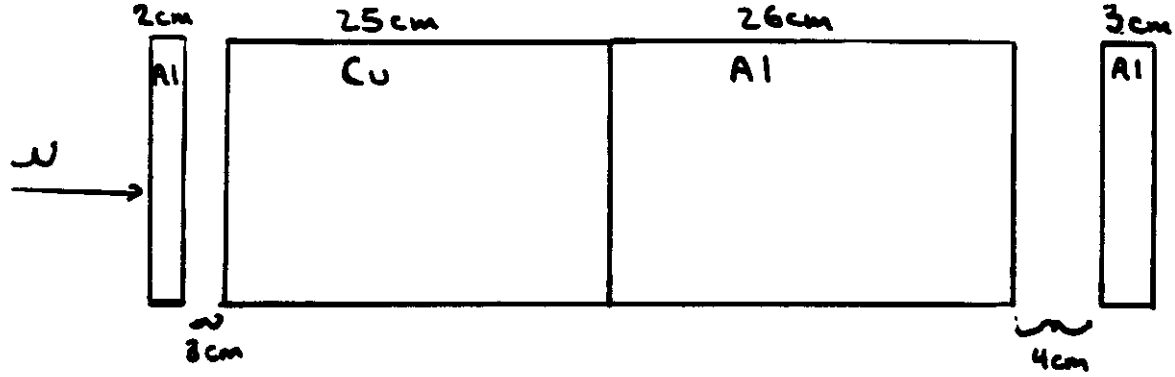
Consider 1st plane after coil at 90°

Detector Geometry

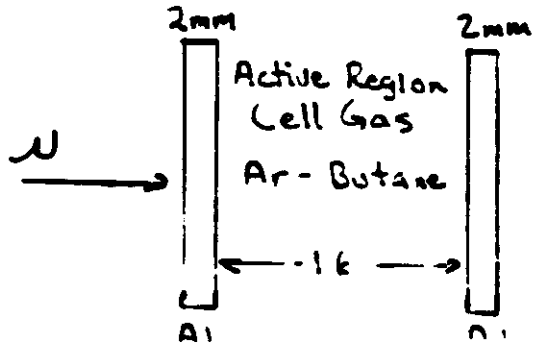


Gaps filled with Air

Coil expanded:

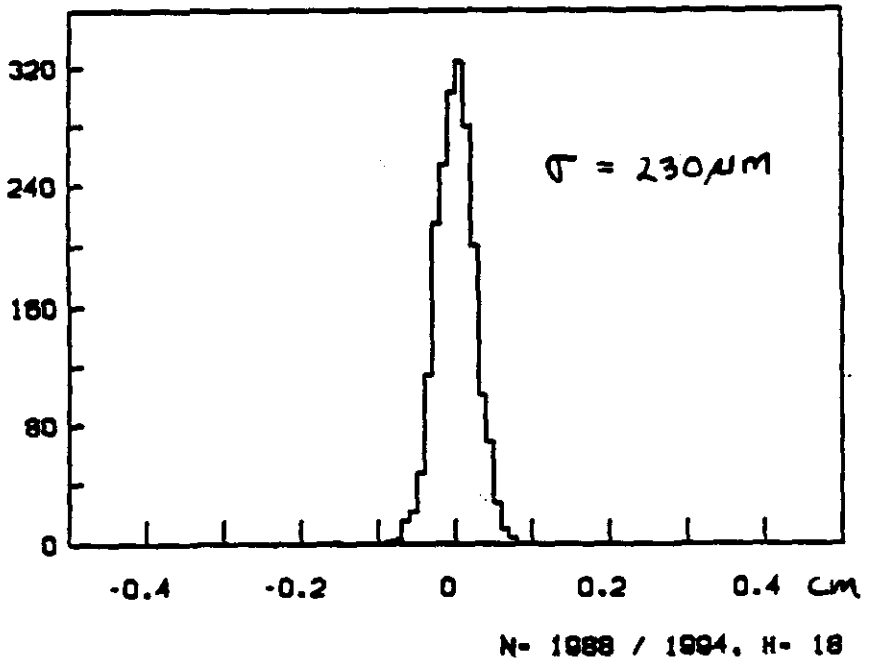


ν Chamber Plane Expanded

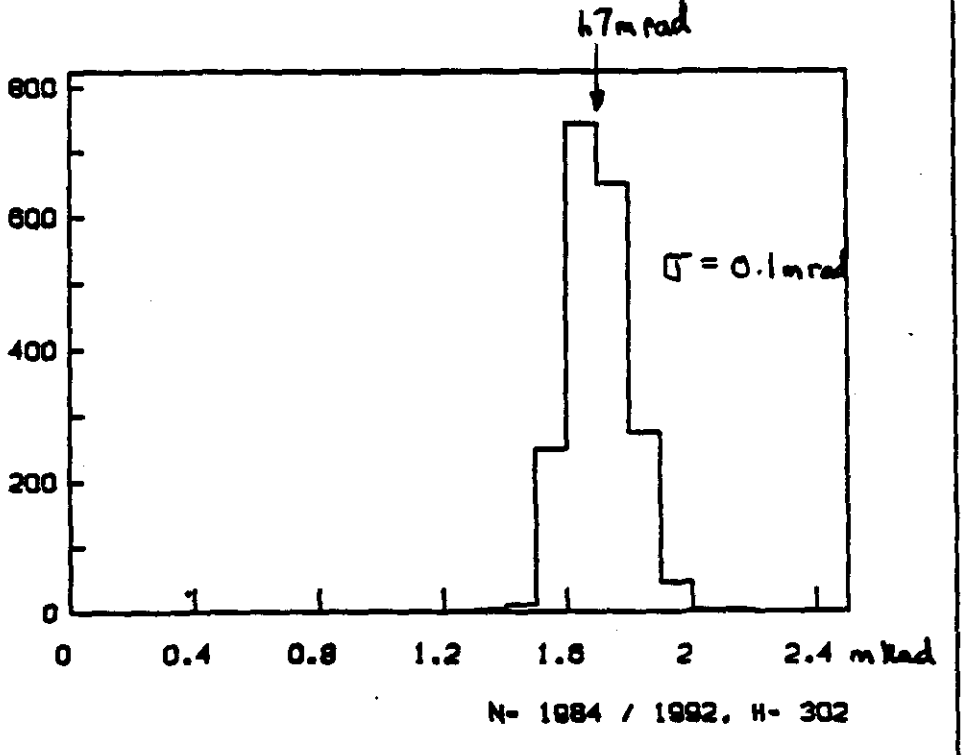


Energy Cutoff In Drift Chamber set at 10 keV for e, γ otherwise set at 1 MeV

1TeV/c Muons at 90degrees GEANT Simulation



Z position at first muon DC (non-bend)



α = Theta_BL (mrad)

Hand Calculations

$\sigma_z = \frac{1}{\sqrt{3}} L \theta_{ms}$

$= 230\mu m$

for $L = 2.7m$

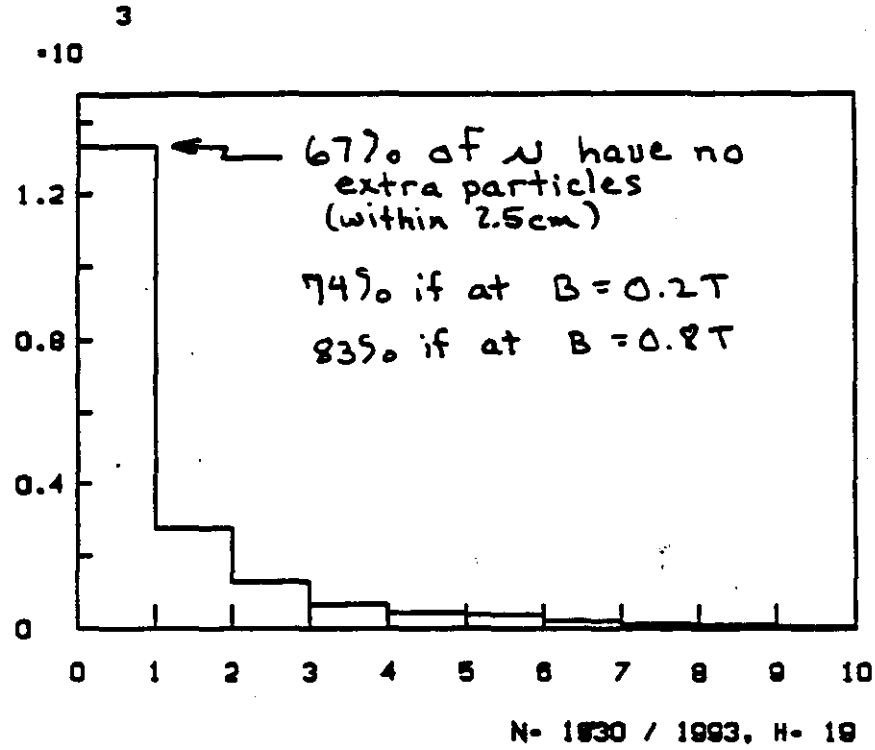
$\alpha = \frac{.3 \times 5T \times 2.2m}{2 \times 1000 GeV}$

$= 1.7 mrad$

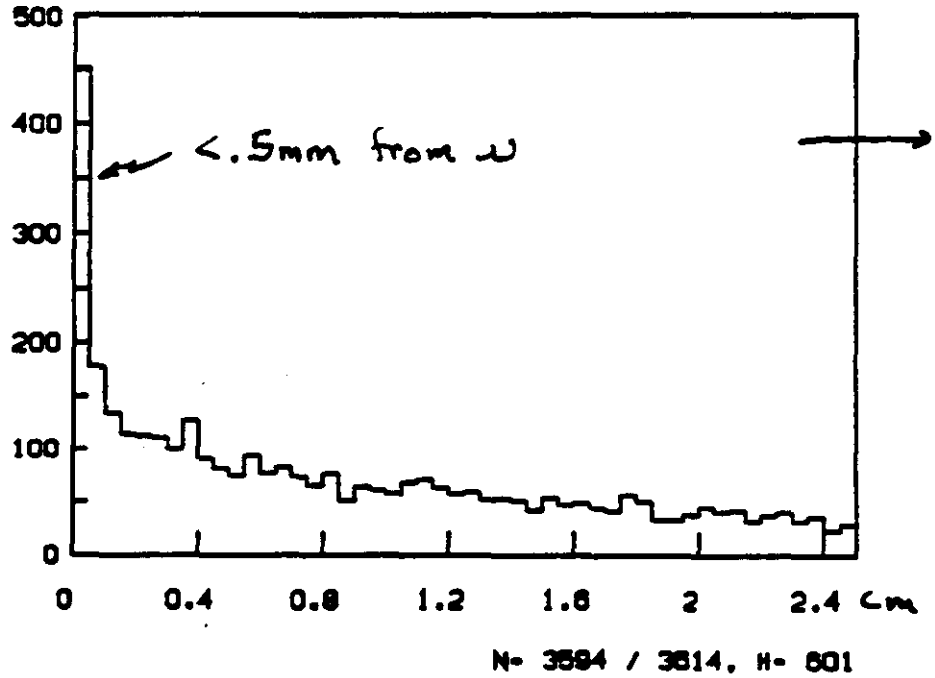
$\theta_{ms} = \frac{.014\sqrt{110}}{1000}$

$= .15 mrad$

1TeV/c Muons at 90degrees GEANT Simulation



Multiplicity of extra particles
(within 2.5cm of ν in bend-plane)

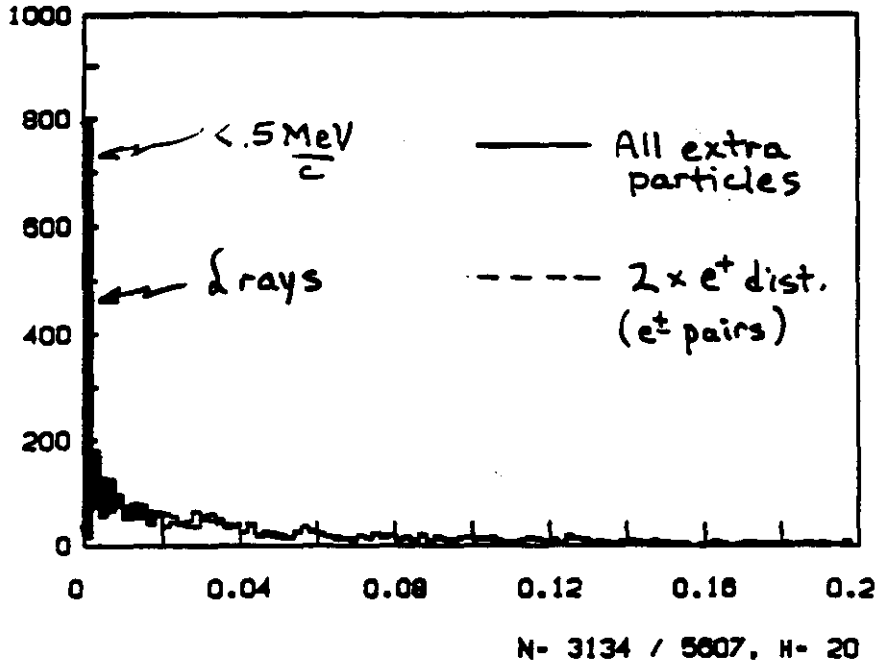


Sep Mu-elec in Bend-plane (cm)
(At initial location in gas)
First chamber after coil
2mm Al wall

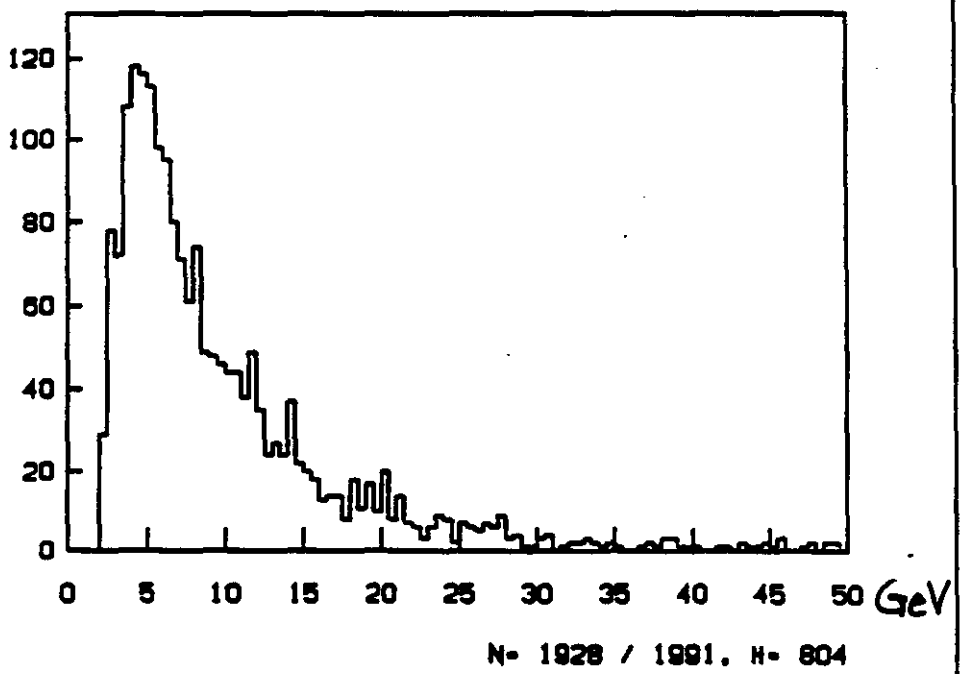
Some of extra particle further from wire that ν.

Now need to extrapola and see if ν measureme compromise

1TeV/c Muons at 90degrees GEANT Simulation



Momentum of extra particles (GeV/c)



Energy loss by Muon in material (Fe_{cal})

First chamber after coil

IV. Cost Estimate (S. Olsen)

- Magnet - From Atiya & Kycia and CMS magnet scale Proper Costing in Progress — $ 100M

- Muon Detectors

Channel counts assuming 2.5cm cells

Barrel	24 layers between coil & iron × 2Z segments	-54K
Barrel	12 layers outside iron × 2Z segments	-48K
	24 layers before iron each end	-15K
	24 layers outside iron each end × 2 segments	-61K
		178K

From EMPACT Costing 178K × $174/chan - Chambers $31M

Gas & Alignment (scaled from E/T) $10M

Total Detectors $41M

- Fe Return 18kton × $2K/Ton — $ 36M

System Total : $ 177M

- End Cap Toroids (only needed for $\eta > 2$)

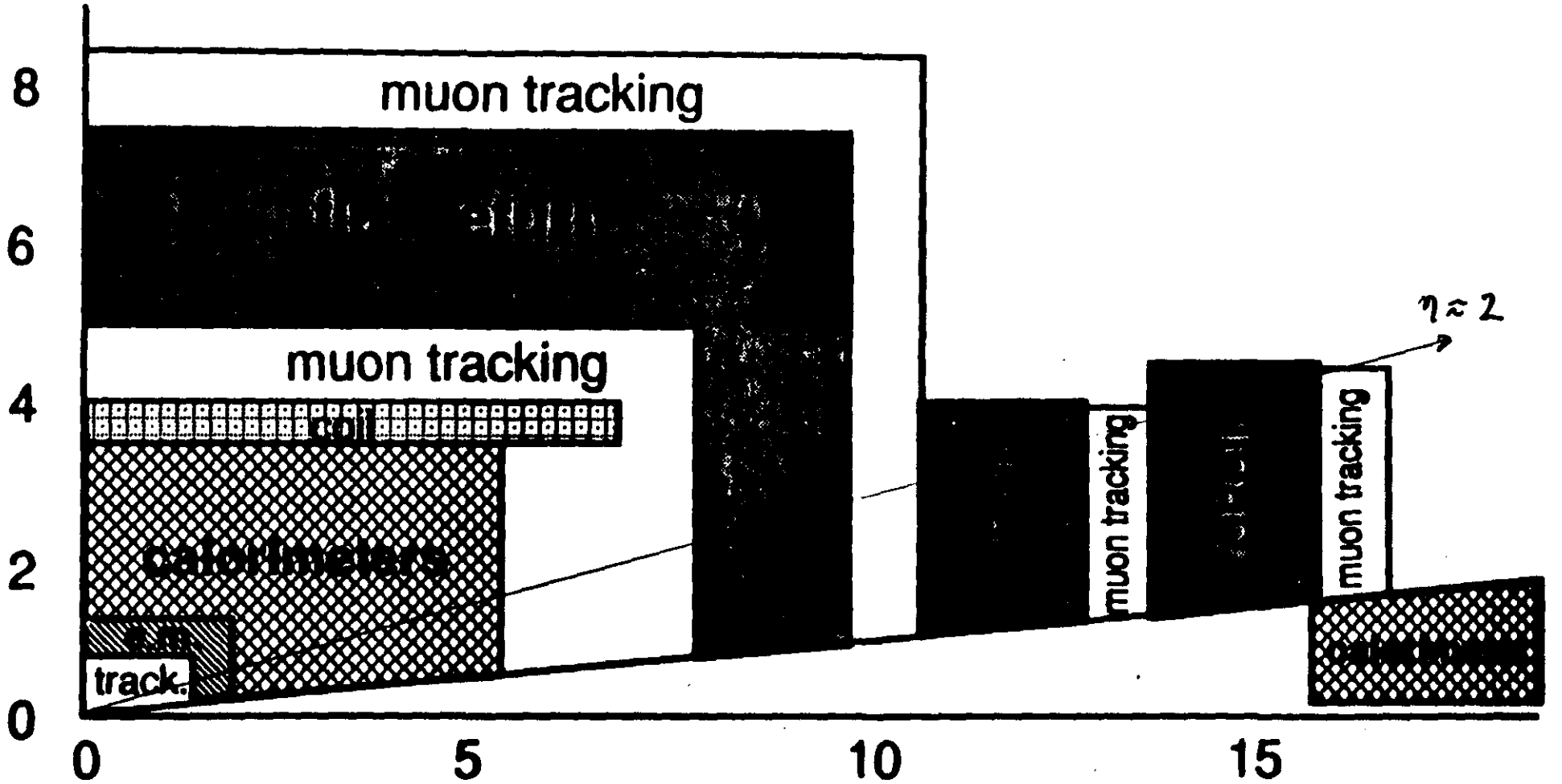
2 Toroids each end R = 5m t = 2m

Fe 4 × 1.25kton = 5kton × $2k/ton — $ 10M

Chambers 24 - 10m × 10m layers (× 2 split) behind each toroid

= 8 × 24 × 1000cm/2.5cm = 77k × $174/ch — $ 13M

End Cap Toroid System + Gas & Alignment $23M



High Field Design for GEM with Forward Toroids

V. Summary and Future Work

Summary of Attributes

- No magnetic Pollution
- Momentum Resolution - Better than GEM baseline for $P_T \gtrsim 300$ GeV/c
  Deteriorates slowly for high P_T
  $< 9\%$ @ 0.5TeV out to $\eta = 2$
- Allignment - Tolerance relaxed from GEM baseline
  Modest requirements ~ 200 μM global allign.
- Robustness - Resolution ~ 6% even without inner trackin
  - Track outside can be linked to track inside. flux return for redundant measurement of track parameters and rejection of backgrounds
  - Simple trigger
- GEM Inner Tracking now at B = 5T
- No Additional Constraints on calorimeter geometry
  《 Want to have low Z radiator 》
  CAL @ 5 Tesla
- Rates/backgrounds - manageable
  - leak field in tracking region will help sweep out low-P δ-rays
  - High Field in Calorimeter reduces hadron bkg
- Costs - $\lesssim$ GEM Baseline
  - Cheaper to add End Cap Toroids

Future Work

- Detailed costing of magnet
- Magnetic field calculation
  ⇓
- Refined Resolution Curves
- Further study of ν backgrounds
  - determine efficiency for measuring high P_T ν
- Homework
  - We invite comments, questions, suggestions
  - Invite detector technology advocates to consider the High field Option in their design reqmts.

Talk by Steve Ahlen
on Engineering Plan

ENGINEERING PLAN

Frank Nimblett + 1 other; Draper Lab:

- Coordination of mech. engineering
- Cost/efficiency comparison in uniform way of various technologies
- Detailed design work on square tube and pad systems

Jack Hanlon + Brian Smith; Los Alamos:

- Global Alignment
- Detailed design work on round tubes

Coleman Johnson; Livermore:

- Coordinate structural engineering involving overlap of muon/magnet systems

Eric Hazen; Boston U.

- Muon System Electronics Concepts
- Muon representative in Trig/DAG eng.

Jim Sullivan ; MIT

- Interacts with magnet and muon groups to translate magnet + detector configurations into p-resolution

- Consider benefits/requirements on combining Central Tracker with muon chambers

Talk by Frank Nimblett
on Engineering Plan for
GEM Muon System

MUON SYSTEM ENGINEERING

MUON GROUP MEETING
AT BOSTON UNIVERSITY
23 AUGUST 1991

GEM MUON SYSTEM
F. Nimblett 8/23/91
Draper Laboratory

GEM MUON ENGINEERING
(Now till Oct. PAC Review)

- Design evaluation for sensor technology options (Performance evaluation, layout practicality, alignability, multiple scattering, operational concepts, costs, processing and assembly procedures, safety issues, risk evaluation)
- Develop muon system support structure concepts to fulfill needs of individual technologies (modular trusses to support measurement groups of three layers of chambers; similar to L*)
- Develop Muon system WBSs (several versions needed to cover options)
- Develop Muon system cost books (several versions needed to cover options) and a uniform costing procedure.
- Develop muon system planning and schedule.
- Coordinate muon related activity with MIT and LLNL who will be working the magnet and with LANL who will be working endcap muon support structure concepts plus a global alignment system.
- Develop local alignment (inter-module) concepts and costs for the sensor specific options of chamber layouts.
- Complete interface hardware concepts (Module to magnet, Chamber to module, Magnet mounted rail system for central region, Endcap muon system attachments)
- Determine facility requirements for specific sensor options (assembly space, gas needs, safety requirements, power requirements, hoist requirements, compatibility with hall parameters)
- Specify system installation and alignment needs, procedures, and costs.

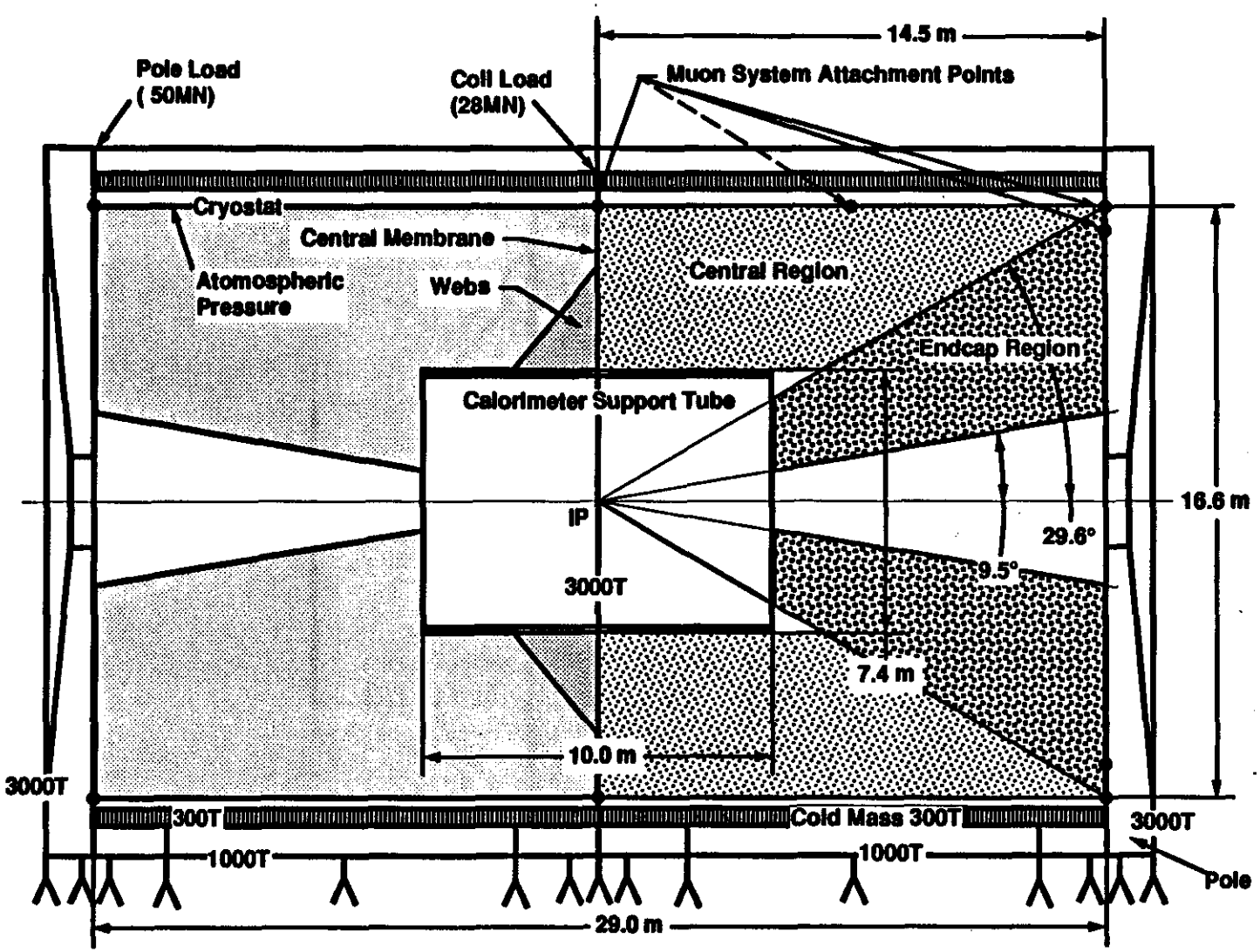
GEM MUON SYSTEM

F. Nimblett 8/23/91

Draper Laboratory

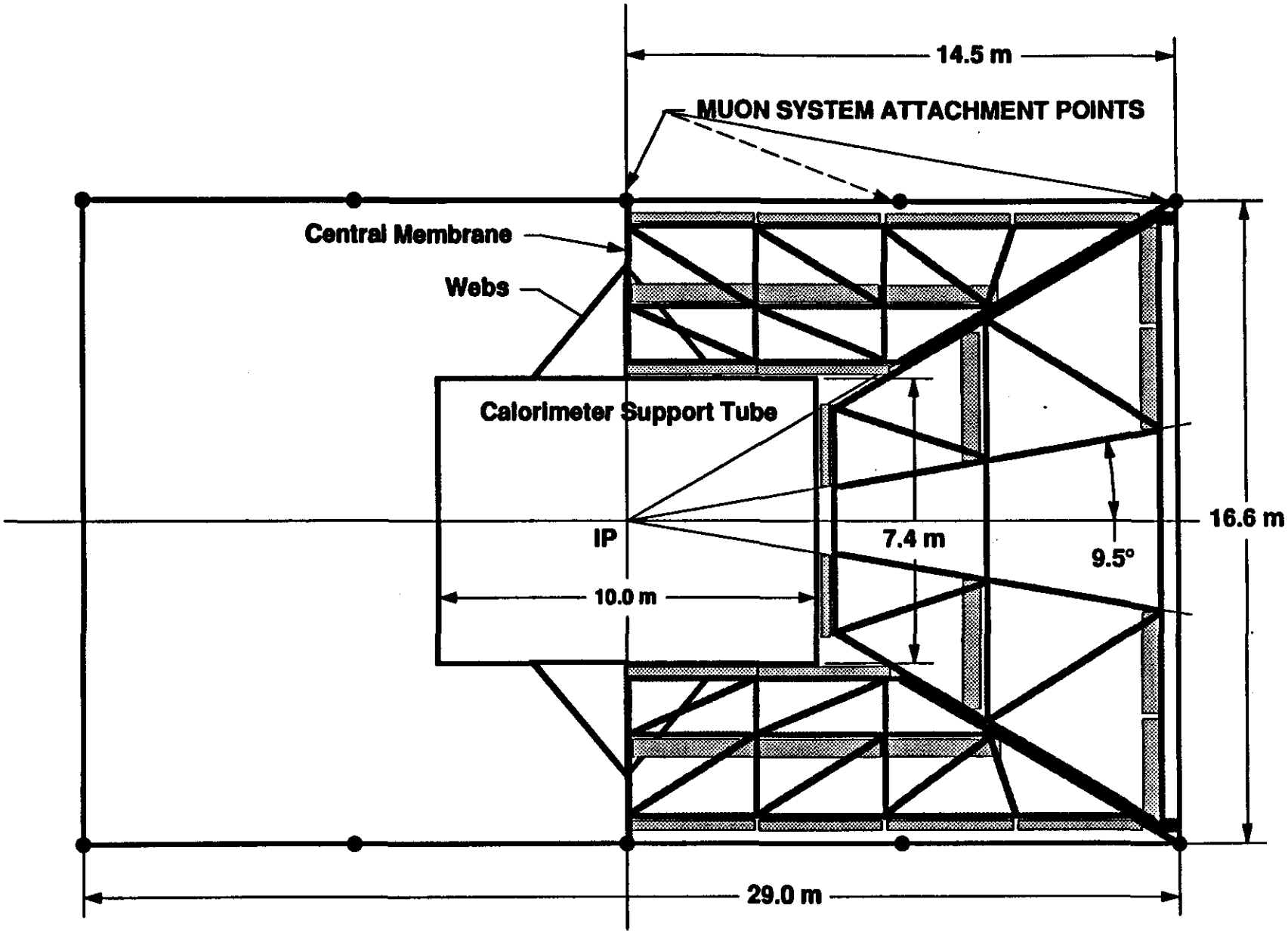
GEM MUON ENGINEERING
(PAC review to LOI)

- Refine all previous efforts in a more focussed manner (Provide additional analysis if viewed as risk factor, improve cost model, improve program planning)
- Preparation of LOI documentation (LOI document plus Presentation vugraphs)
- Preparation for increased levels of effort to fulfill task of preparing the Engineering Design Report (EDR)



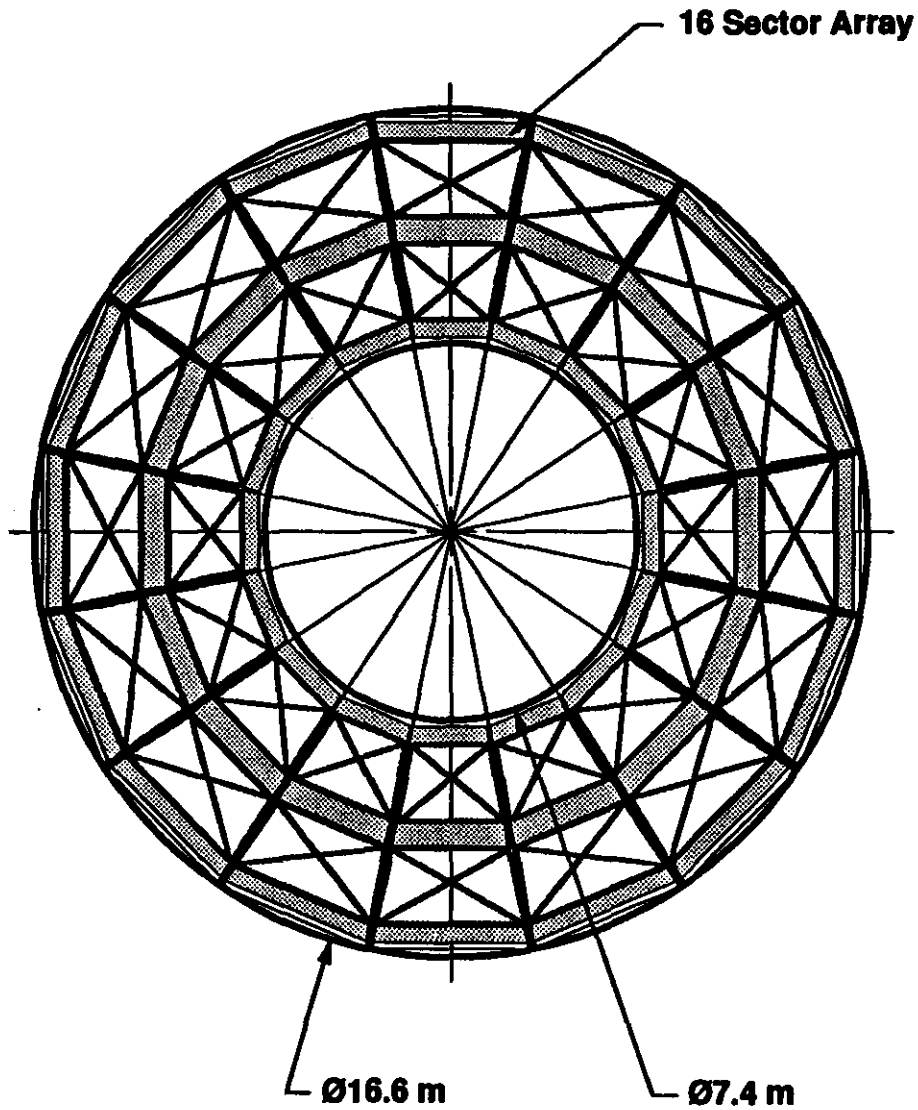
Elevation of GEM Magnet/ Muon System

F. Nimblett 8/21/91



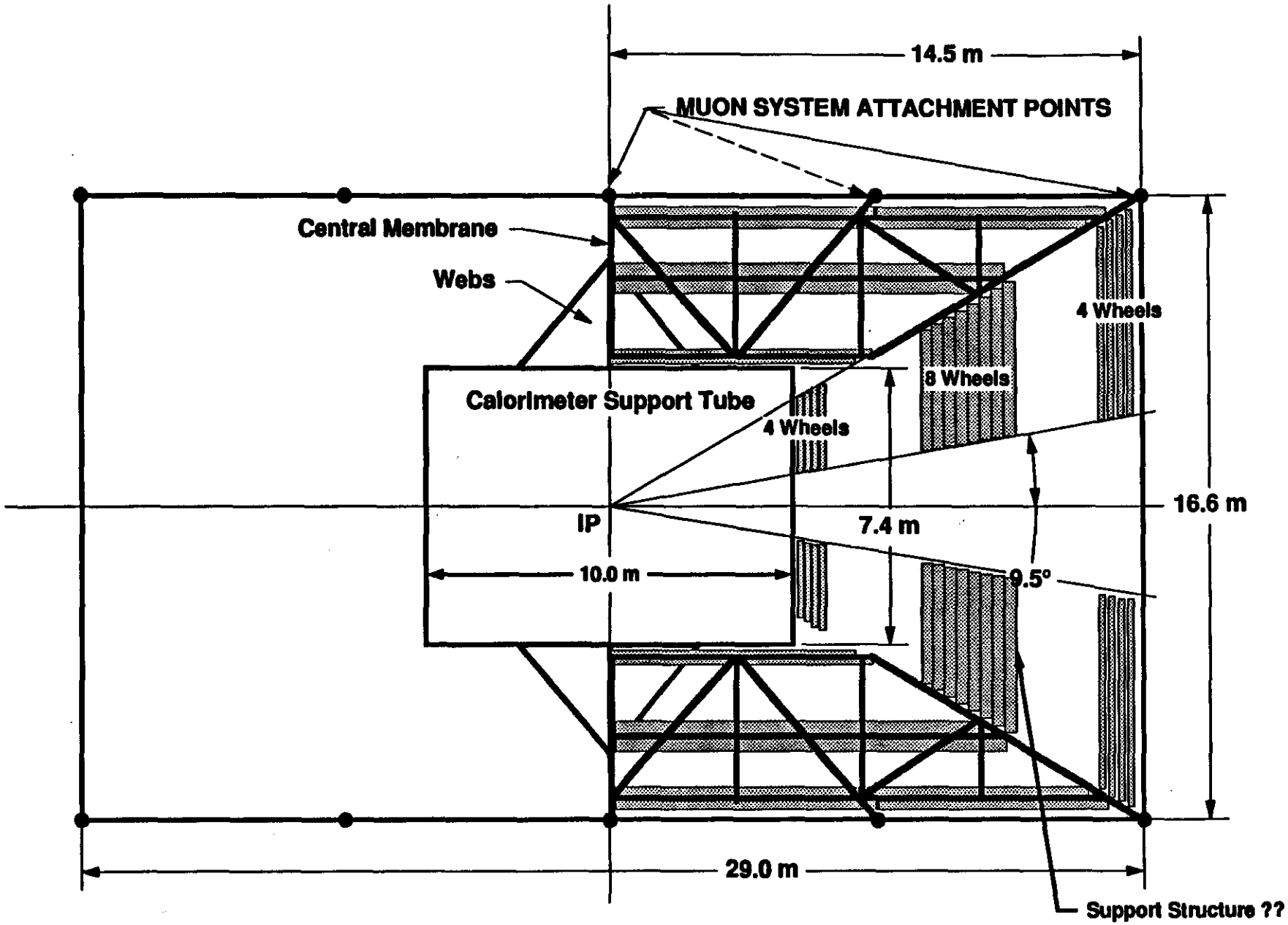
ELEVATION OF PDT MUON SYSTEM

F. Nimblett
21 August 1991



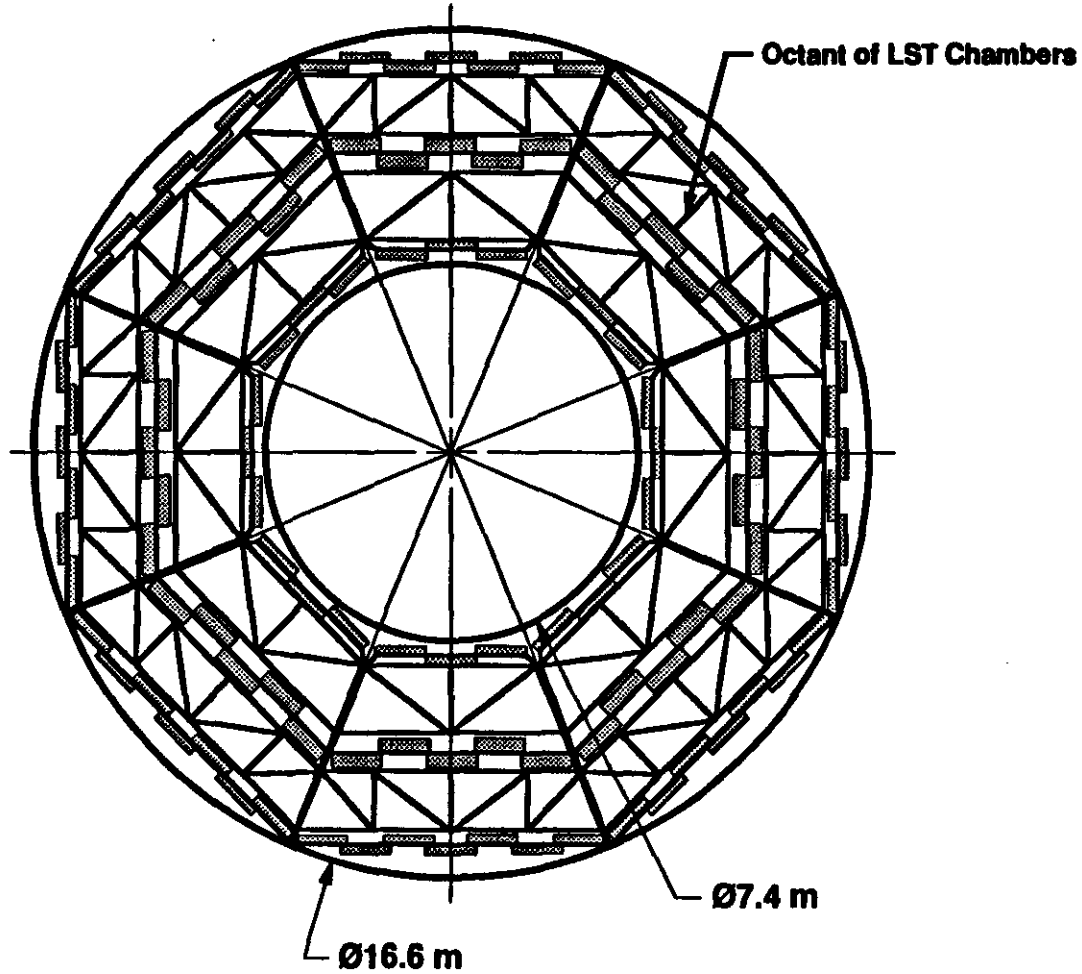
END VIEW PDT MUON SYSTEM
(Central Region shown with support structure)

F. Nimblett
21 August 1991



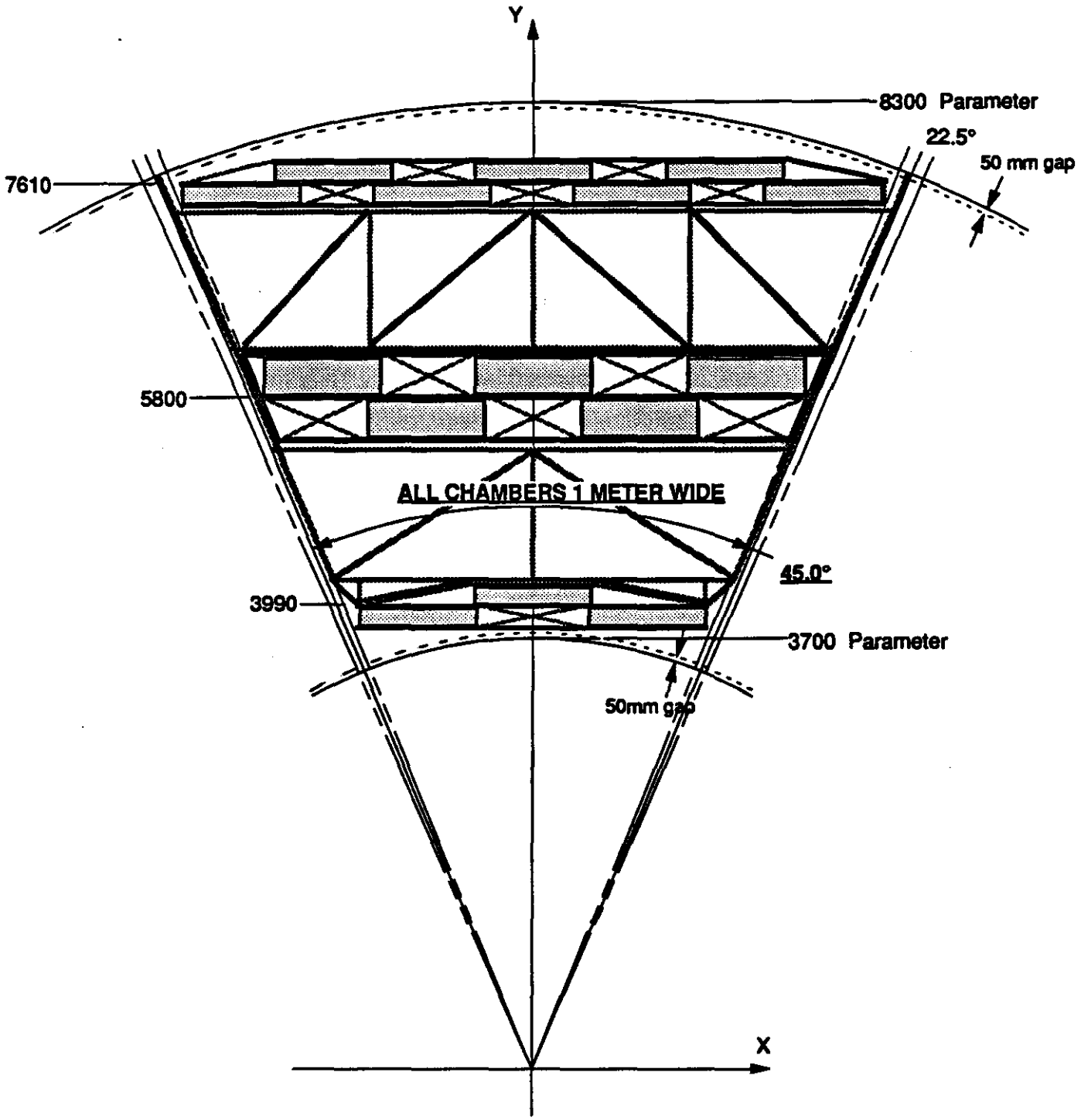
ELEVATION OF LST MUON SYSTEM

F. Nimblett
22 August 1991



END VIEW LST MUON SYSTEM
(Central Region shown with support structure)

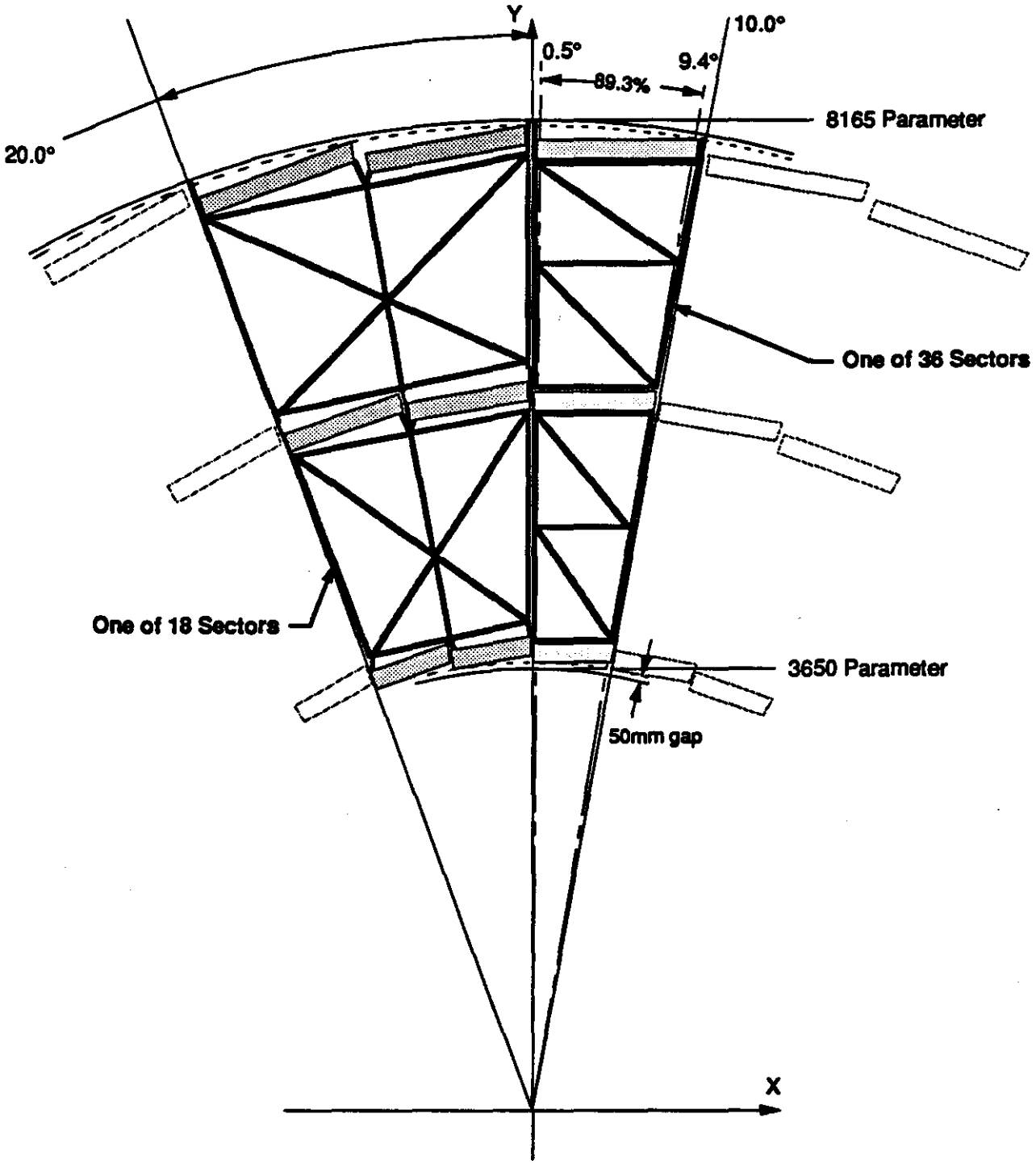
F. Nimblett
22 August 1991



Limited Streamer Tube Muon System

Central Region Section

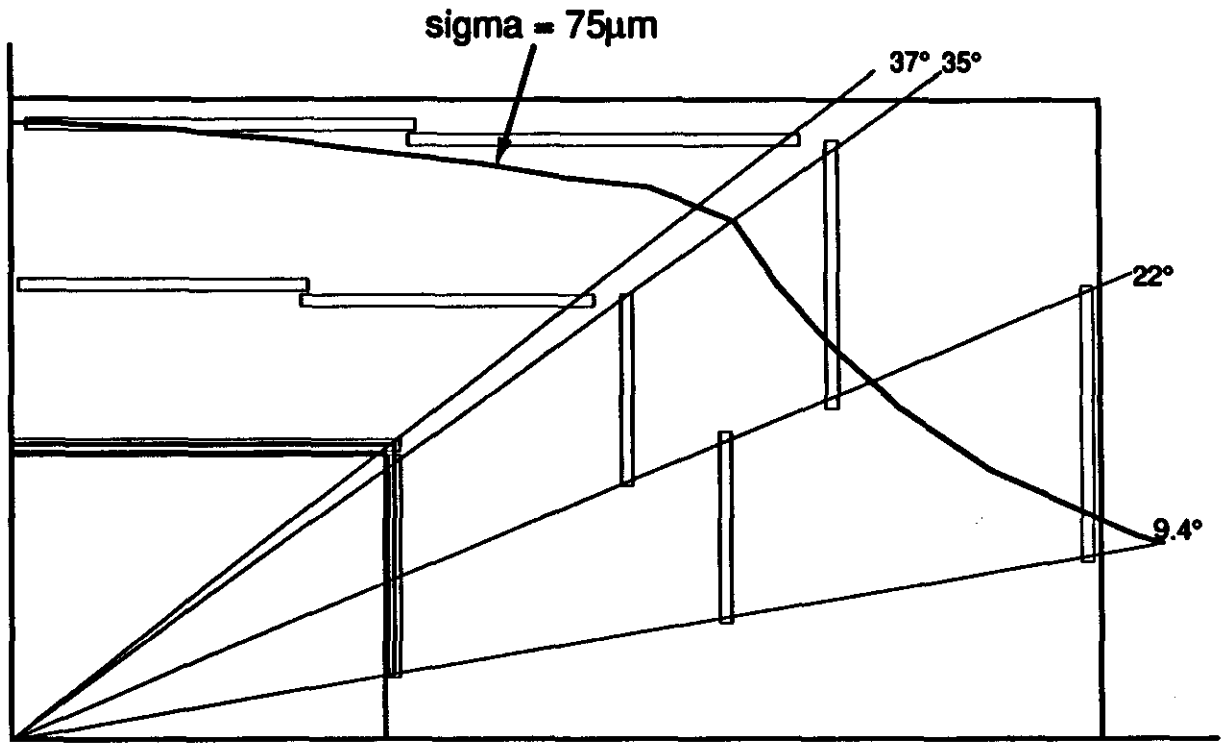
F. Nimblett - LST Study.2
19 Aug 91
Scale 1:50



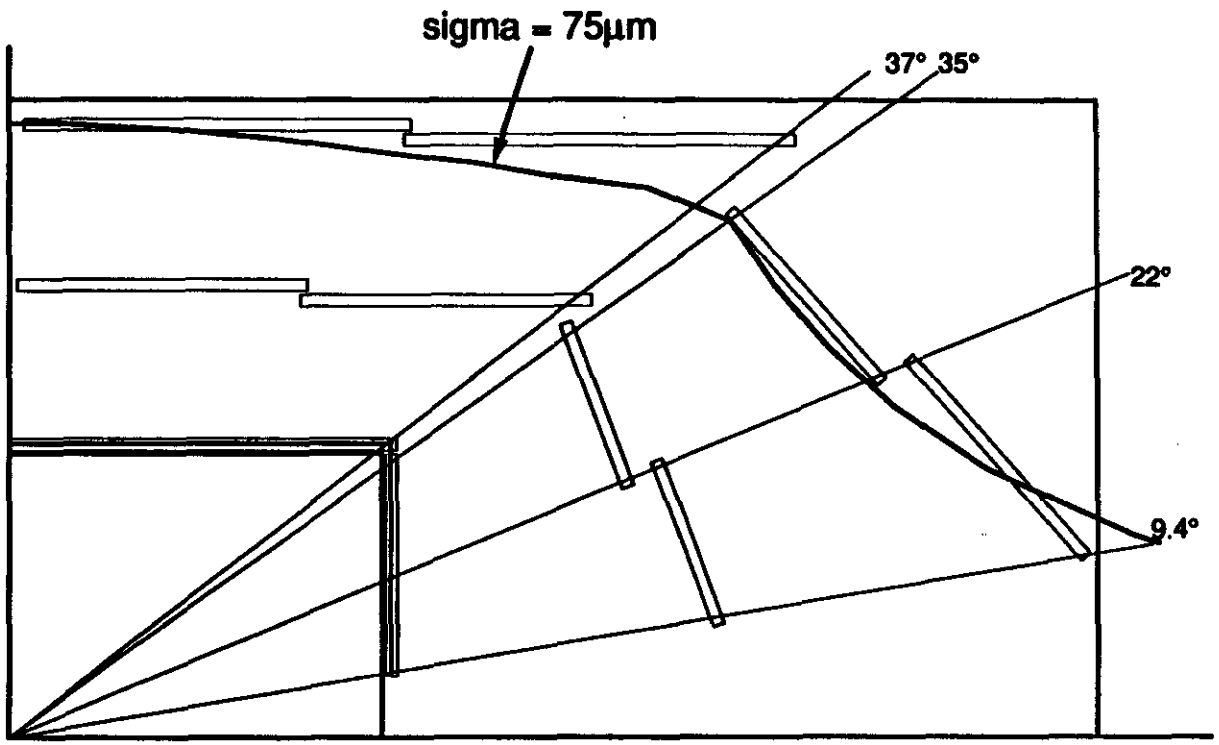
Gas Pad Muon System

Central Region Section

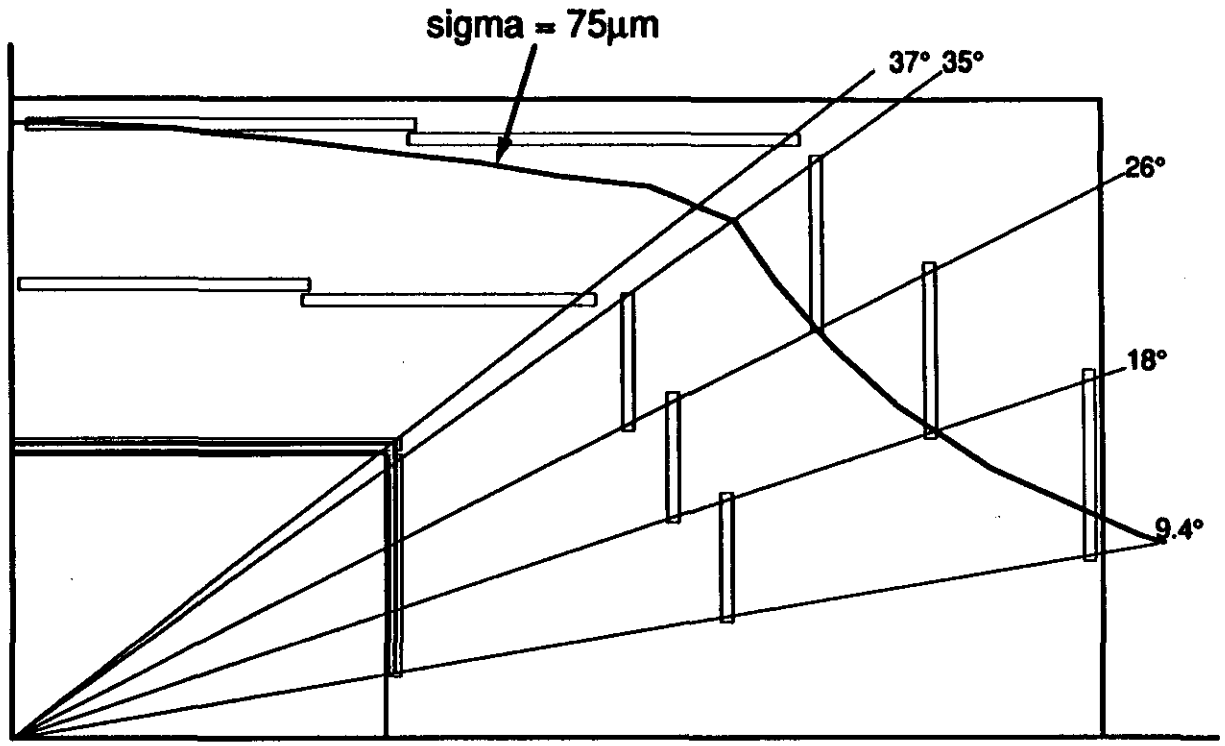
F. Nimblett- Study.2
21 August 1991
Scale 1:50



Gas Pad Layout.3
CG - 19.08.91
1:100



Gas Pad Layout.4
CG - 19.08.91
1:100



Gas Pad Layout.5
CG - 19.08.91
1:100

GEM MUON SYSTEM
SUPPORT STRUCTURES

- Central Region Muon System/Magnet Interface Options
  - Four or six point mount to either two or three substantial rings at the ends of SC magnet cryostat sections (isolated from cryostat wall radial deformations caused by evacuation of cryostat)
  - Space-frame structure hung from similar sites or from the central membrane (Further isolation from magnet and elimination of reaction torques on magnet structure)
  - Unitize modules following assembly (join inner diameters of modules to minimize reaction torques on magnet structure)
- Endap Region support still appears to be best near OD of magnet poles (small axial motion at magnet turn-on plus muon system counterbalanced with pole weight)
- Endcap rotory mount/assembly fixture still appears to be a necessary structure to evaluate to permit vertical loading of endcap modules.

F. Nimblett 8/23/91
Draper Laboratory

GEM MUON
SUPPORT STRUCTURES

- Main thrust of support structure design will continue to be a bolted and pinned truss assembly fabricated from 6061-T6 aluminum tubing and cast aluminum joint hardware.
- Consideration of thinner plate-structures around the middle chambers to provide additional space for these chambers will be a priority!
- Preliminary Weight estimates for the <u>central region assembly</u> of several chamber technologies are promising.
  - L* -- 160 tons
  - PDTs (SSt-- 122 tons) (Alum-- 86 tons) (Myl- 71 tons)
  - LST (Extr. cath.- 250 tons) (Folded cath- 161 tons)
  - GP (Not yet done, probably the lighest!)

Talk by Jack Hanka

on Alignment Strategies

Alignment

- General Considerations for LOI.
- Alignment Techniques.

Jack Hanlon
Los Alamos.

MUON CHAMBER ALIGNMENT

for the LOI

Concept Sketches and Tolerances

* Sector Assembly
* Sector Assembly to Space Frame
* Global Interface
  -- *space frame to beam line*
* Alignment Maintainence
  -- *internal and external*

Description of Tools and Techniques

* LED-lens-detector
* Laser beacon
* Conventional optical tooling
  alignment telescopes, theodolites, interferometers and tooling balls
* Electronic levels
* Fiber optics and speckle
* TV holography

MUON CHAMBER ALIGNMENT

ALIGNMENT TASK	STARTING POINT CONCEPTS
* SECTOR ASSEMBLY	System Dependent *Combination of conventional tooling and gadget development*
* SECTOR TO SPACE FRAME	LED - Lens - Detector *used on L3, but perhaps more than 3 bridges for GEM*
* GLOBAL INTERFACE	Basic Installation Task *Planned conventional tooling*
* ALIGNMENT MAINTAINENCE	Electronic levels Fiber Optics/Speckle *Development Task*

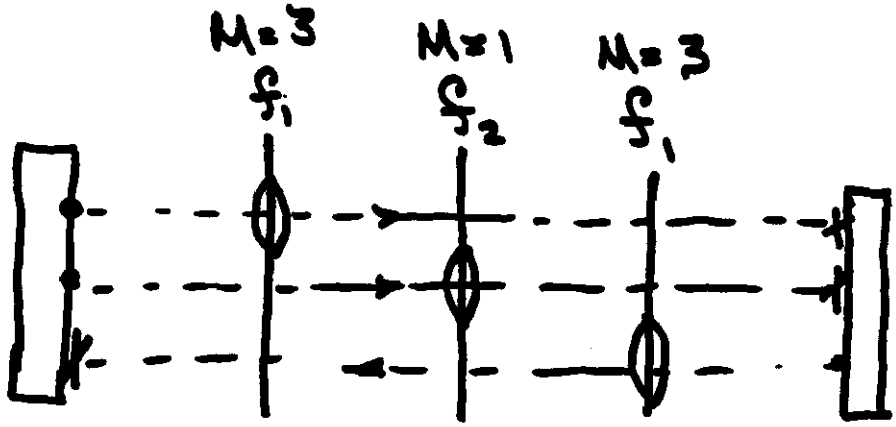
VARIABLE	*RESOLUTION*
Alignment Telescopes	~ 15 μrad
Precision Theodolites	~ 3 μrad
Precision Electronic Levels	~ 3 μrad
Precision Electronic Autocollimators	~ 0.1 μrad
Hewlett Packard Interferometer	~ 0.05 micron
Linear Moire Scales	~ 0.5 micron
Camera's and Centroid Software	~ 0.1 micron
Visual Instruments	~ 1 micron
Cordex Measuring Machine	~ 2 micron

LED-LENS-DET.

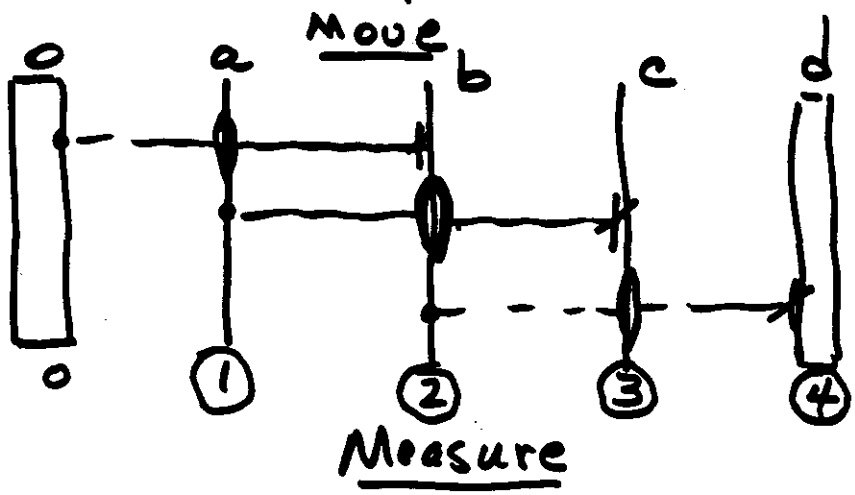
Motion (ϵ)	Measure
S	ϵ
L	2ϵ
D	ϵ

Not sensitive to tilt of any component.

Multiple Bridges.



Another Approach



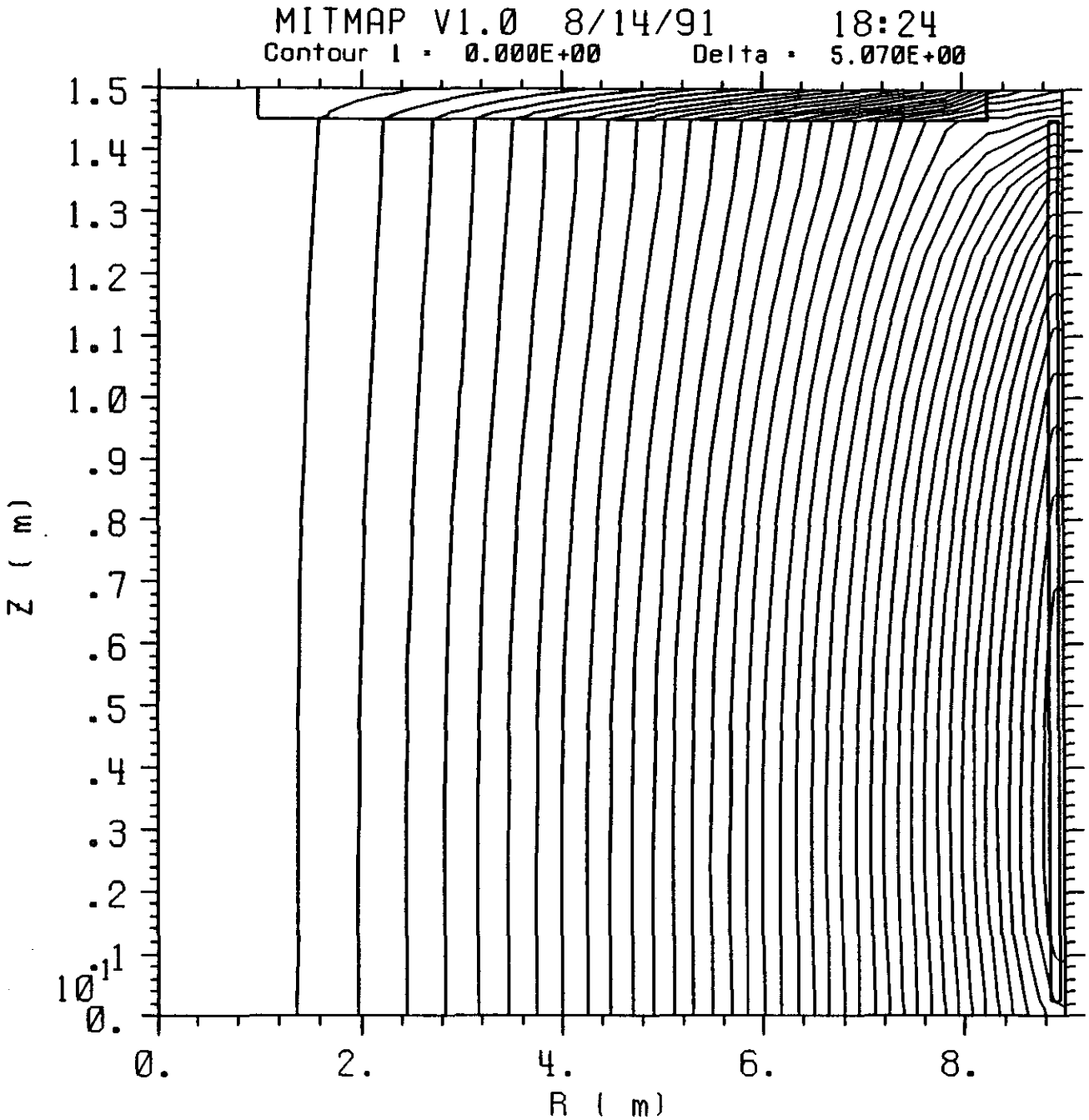
$$o + b + 2c = 4$$
$$a + 2b + c = 3$$
$$2a + b + o = 2$$

Solve for a, b, c

<u>Extendable</u> to any # of bridges.

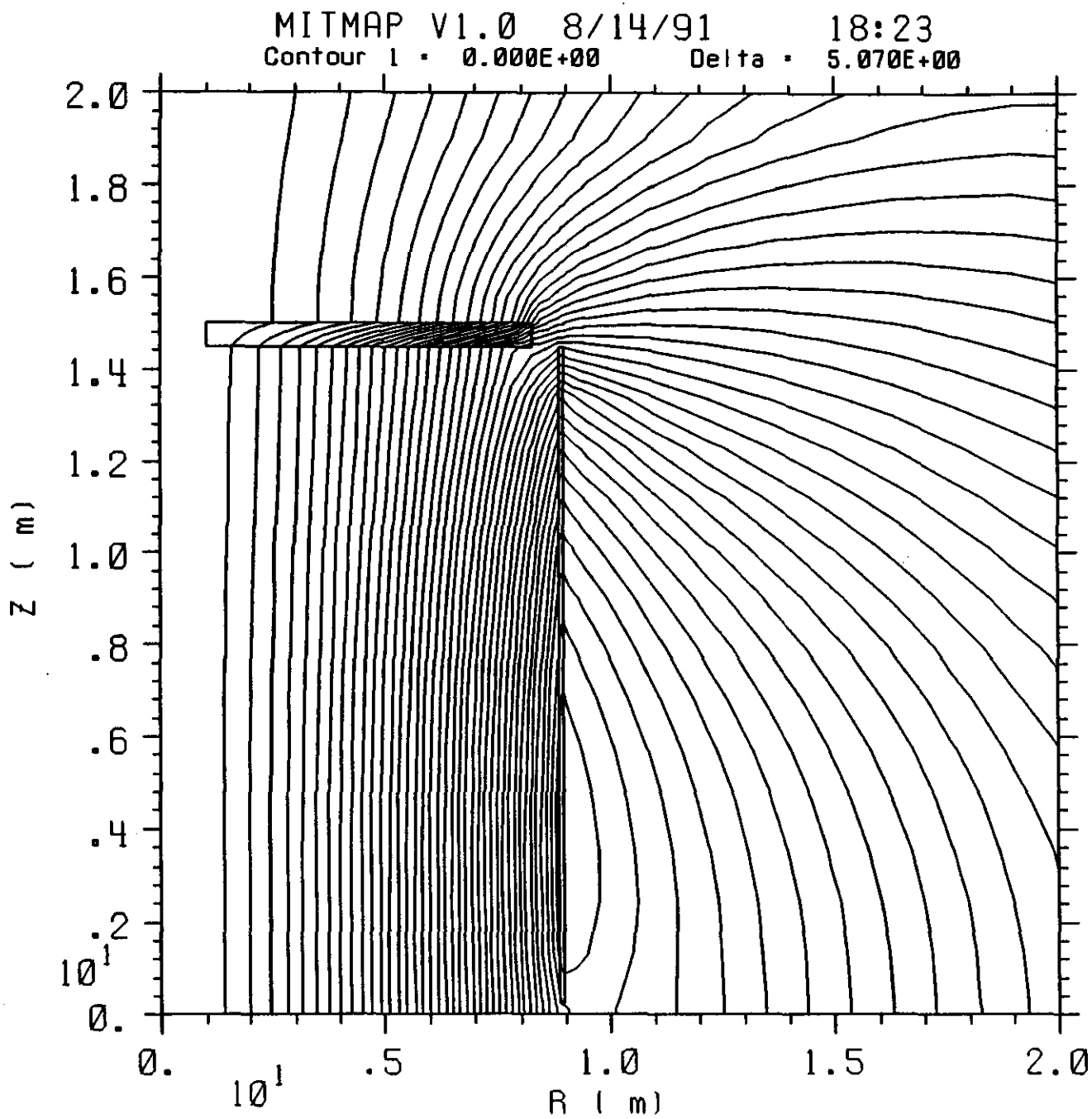
Talk By Jim Sullivan
on Magnetic Field Calculations
and on Momentum Resolution
Calculations

GEM --- Thin Pole Options: Case 3



CONTOURS OF CONSTANT FLUX

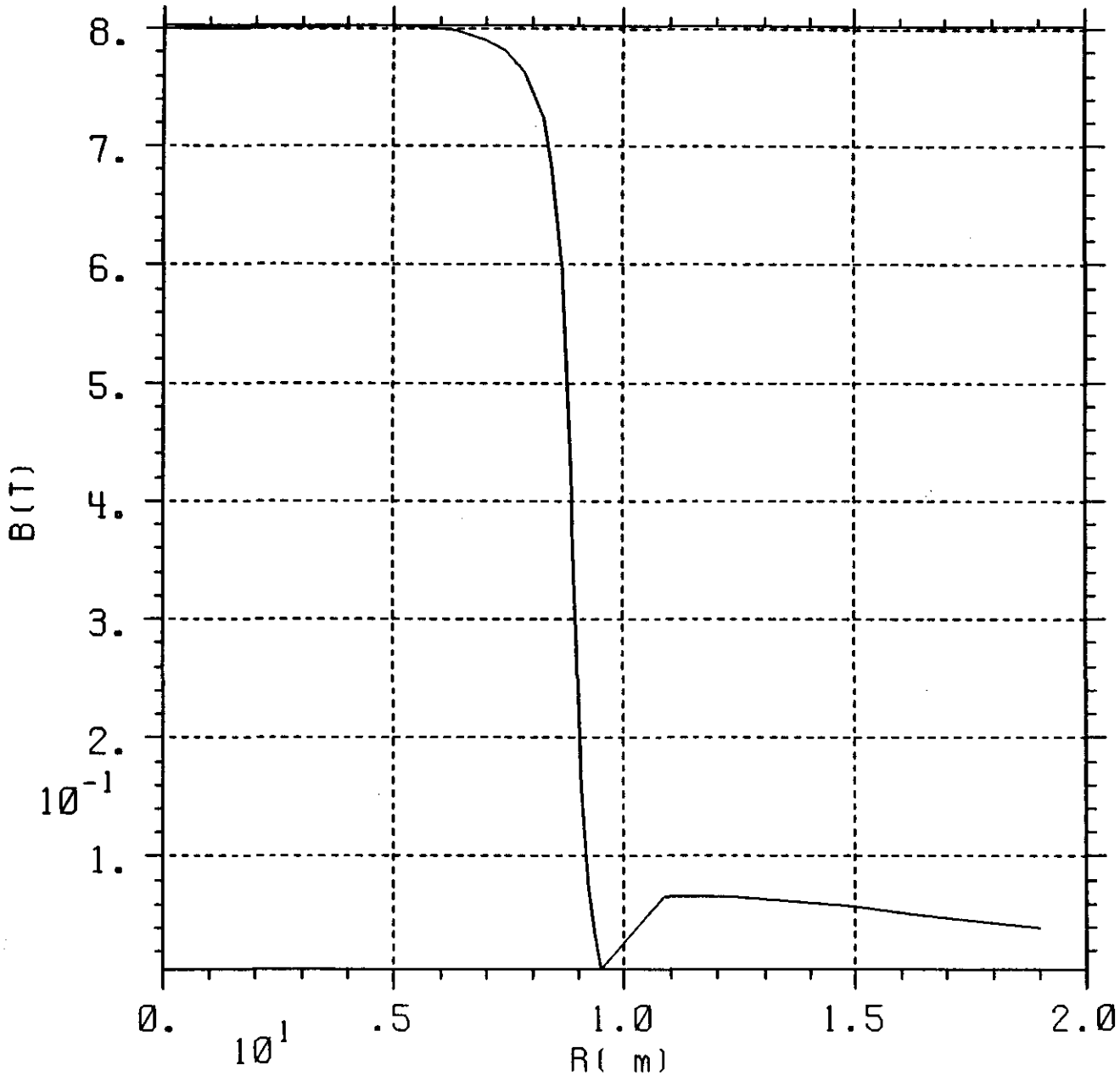
GEM --- Thin Pole Options: Case 3



CONTOURS OF CONSTANT FLUX

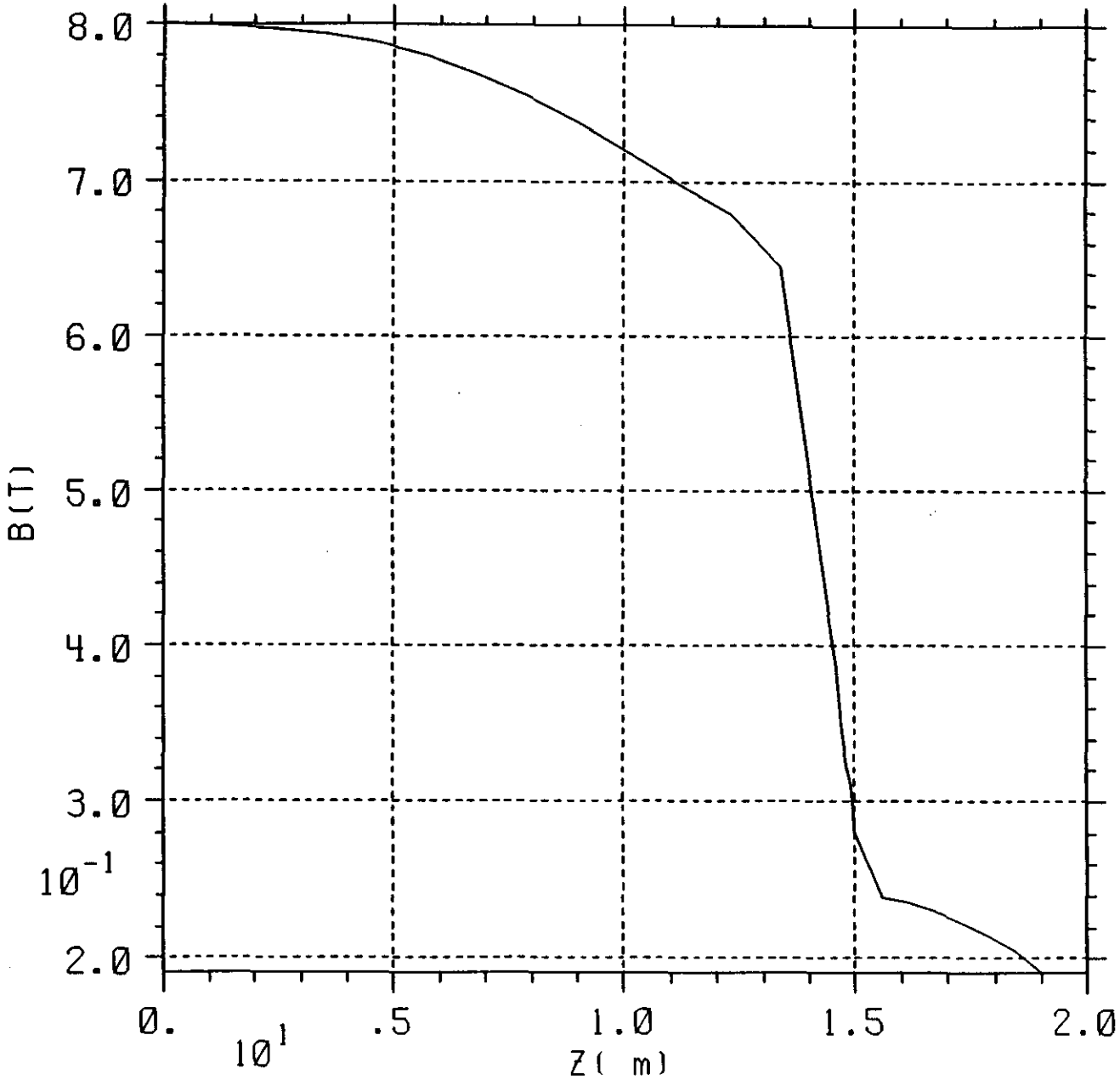
GEM --- Thin Pole Options: Case 3

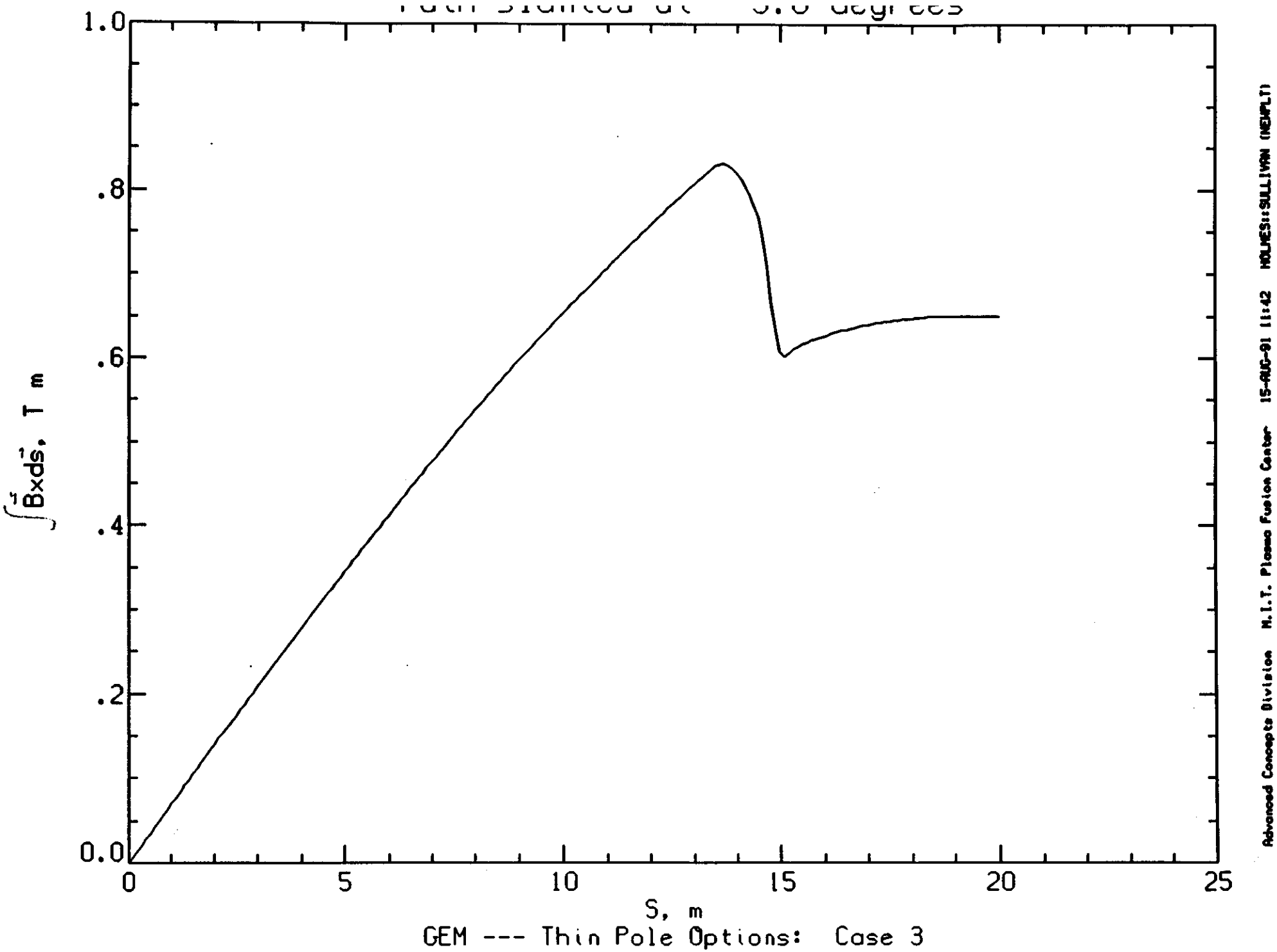
MITMAP V1.0 8/14/91 18:25

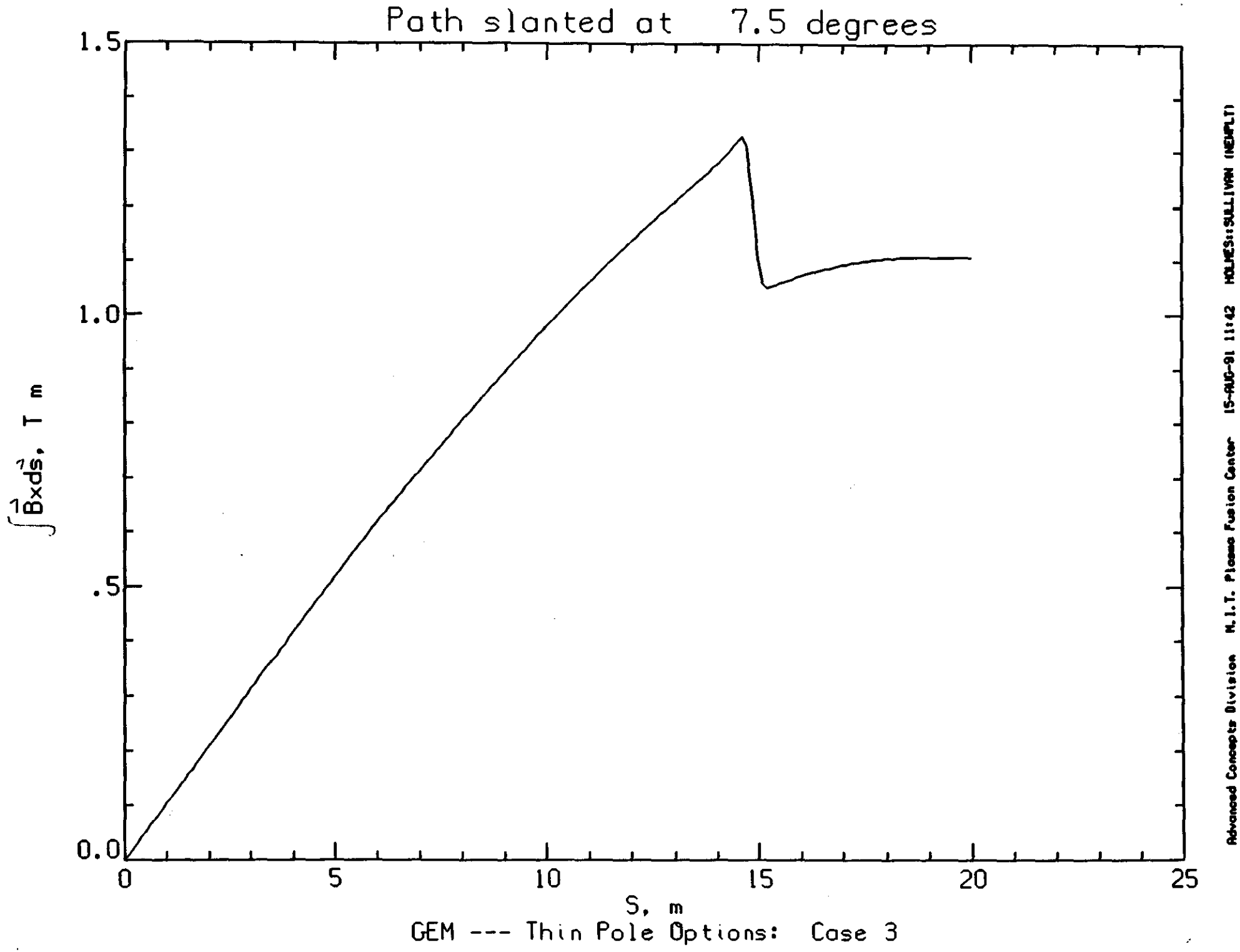


GEM --- Thin Pole Options: Case 3

MITMAP V1.0 8/14/91 18:25




Path Started at 0.0 degrees
1.0
.8
.6
.4
.2
0.0
0
5
10
15
20
25
S, m
$\int_1^2 B \times ds$, T m
GEM --- Thin Pole Options: Case 3
Advanced Concepts Division M.I.T. Plasma Fusion Center 15-AUG-91 11:42 HOLMES::SULLIVAN (NEMPLT)


Path slanted at 7.5 degrees
1.5
1.0
.5
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5
10
15
20
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S, m
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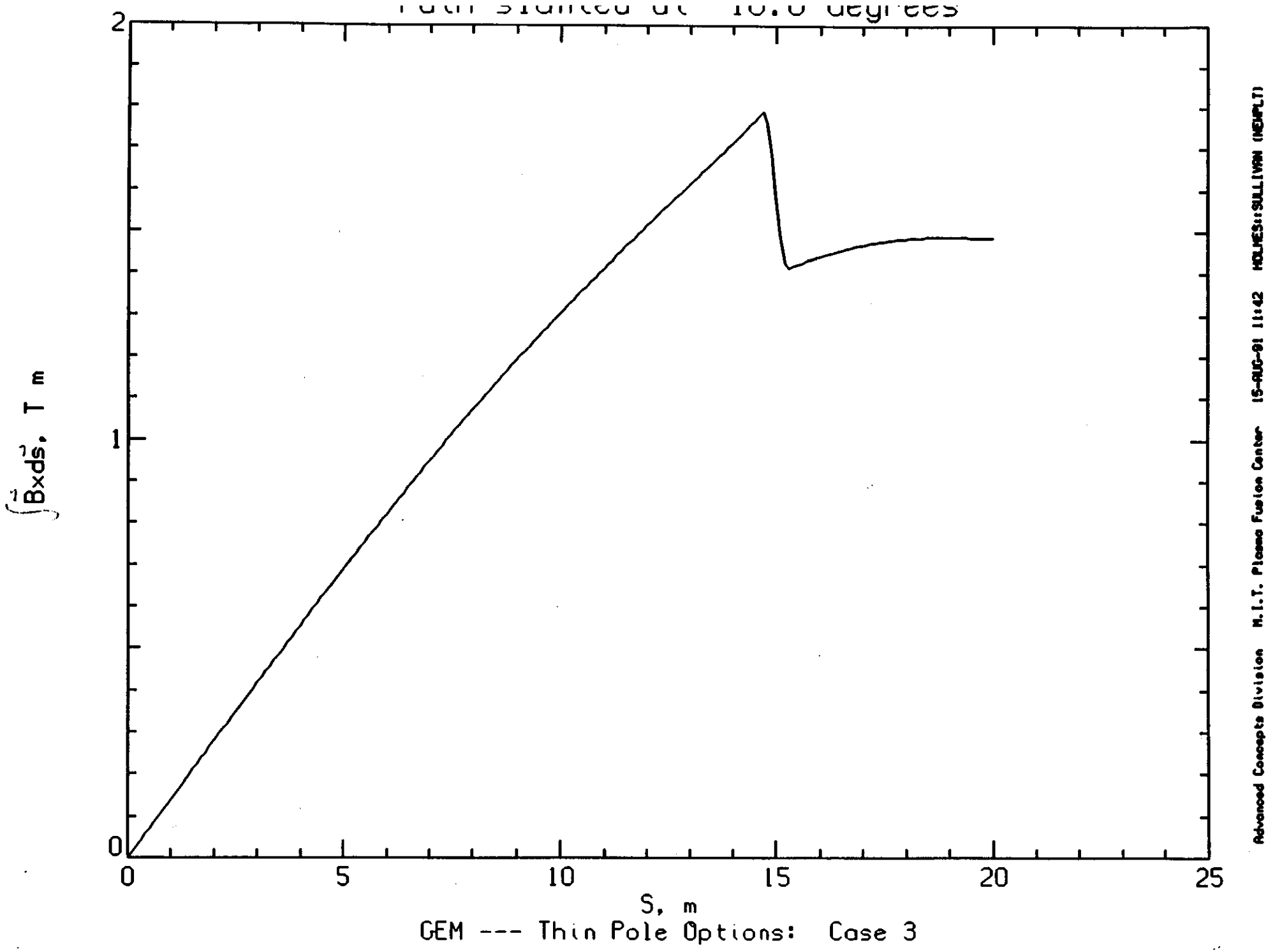
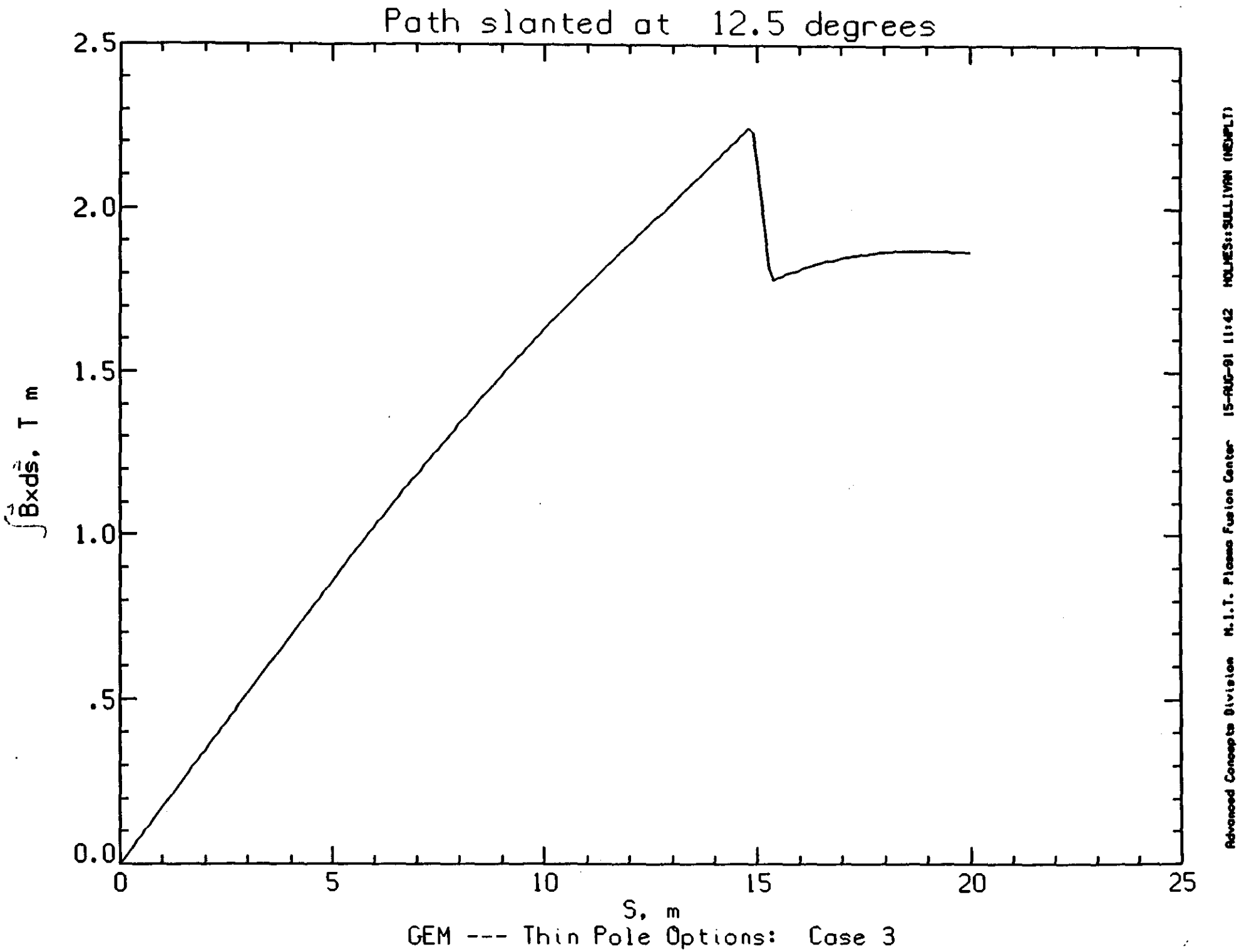
GEM --- Thin Pole Options: Case 3
Advanced Concepts Division M.I.T. Plasma Fusion Center 15-AUG-91 11:42 HOLMES::SULLIVAN (NEWPLT)



GEM --- Thin Pole Options: Case 3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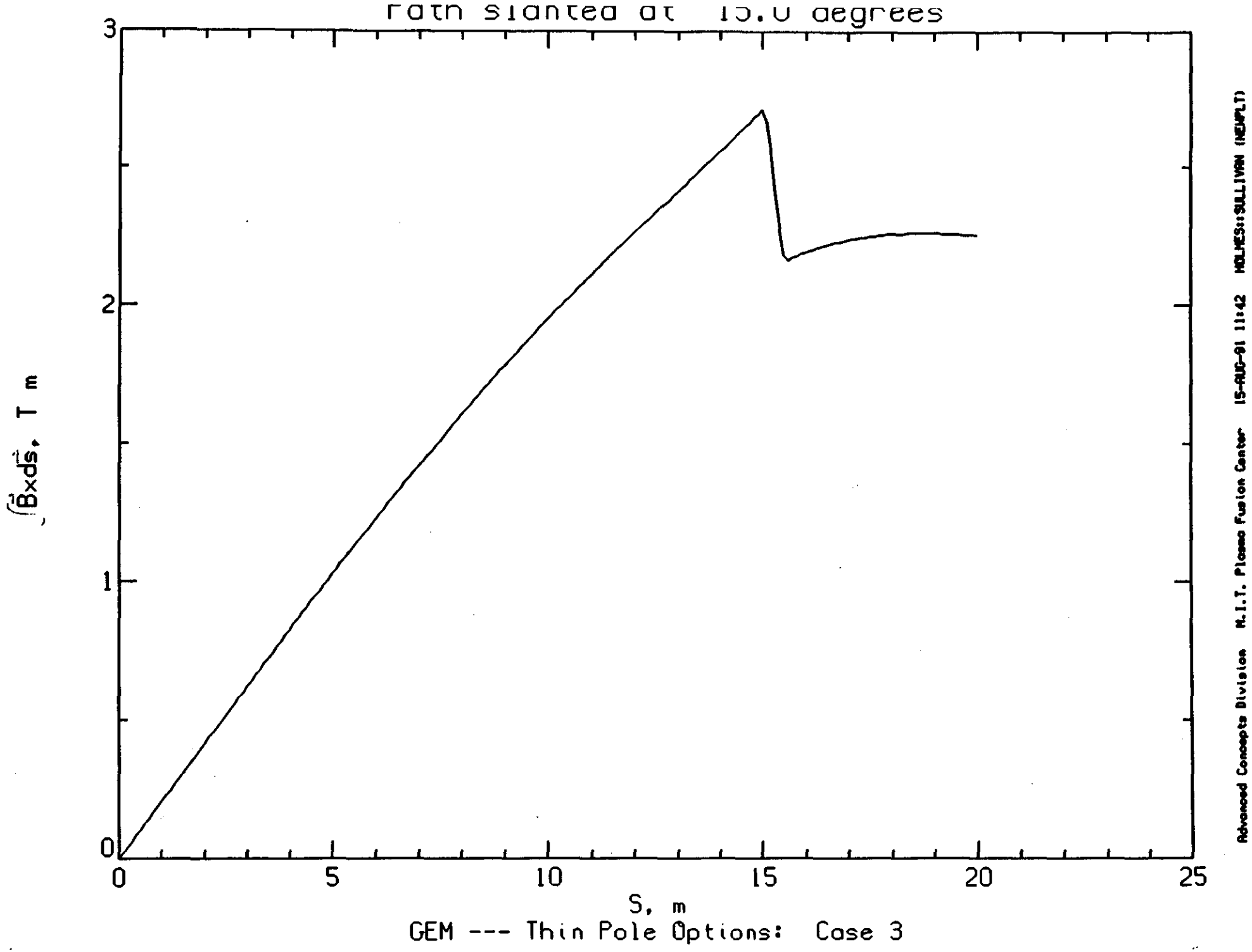
1.5
1.0
.5
0.0
0
5
10
15
20
25
S, m
$\int \vec{B} \times d\vec{s}$, T m
GEM --- Thin Pole Options: Case 3
Advanced Concepts Division M.I.T. Plasma Fusion Center 15-AUG-91 11:42 HOLMES::SULLIVAN (NEWPLT)


Path slanted at 15.0 degrees
$\int \vec{B} \times d\vec{s}$, T m
S, m
0
1
2
3
0
5
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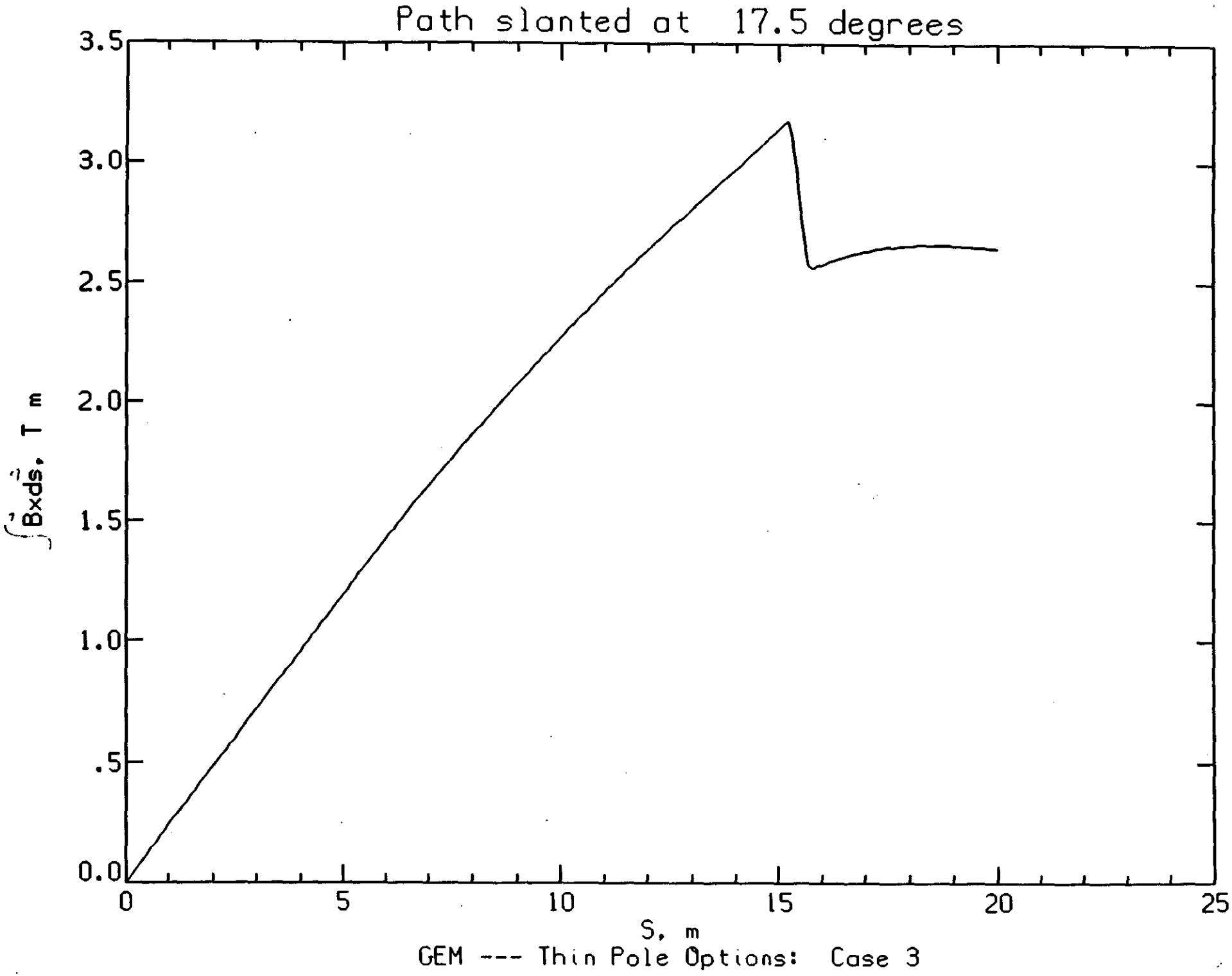
15
20
25
GEM --- Thin Pole Options: Case 3
Advanced Concepts Division M.I.T. Plasma Fusion Center 15-AUG-91 11:42 HOLMES::SULLIVAN (NEMPLT)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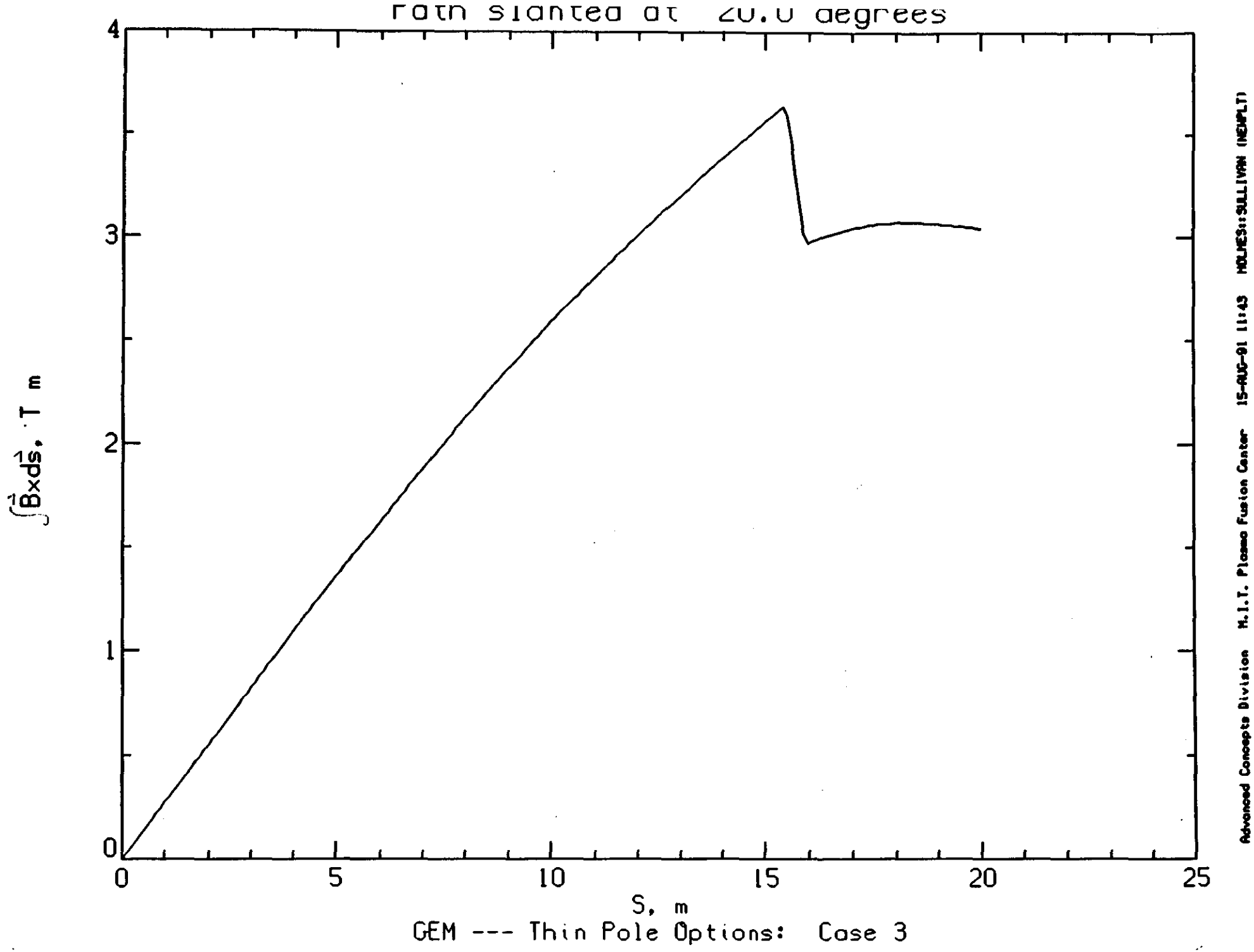
1.0
.5
0.0
0
5
10
15
20
25
S, m
$\int \vec{B} \times d\vec{s}$, T m
GEM --- Thin Pole Options: Case 3
Advanced Concepts Division M.I.T. Plasma Fusion Center 15-AUG-91 11:43 HOLMES::SULLIVAN (NEWPLT)


Path slanted at 20.0 degrees
$\int \vec{B} \times d\vec{s}$, T m
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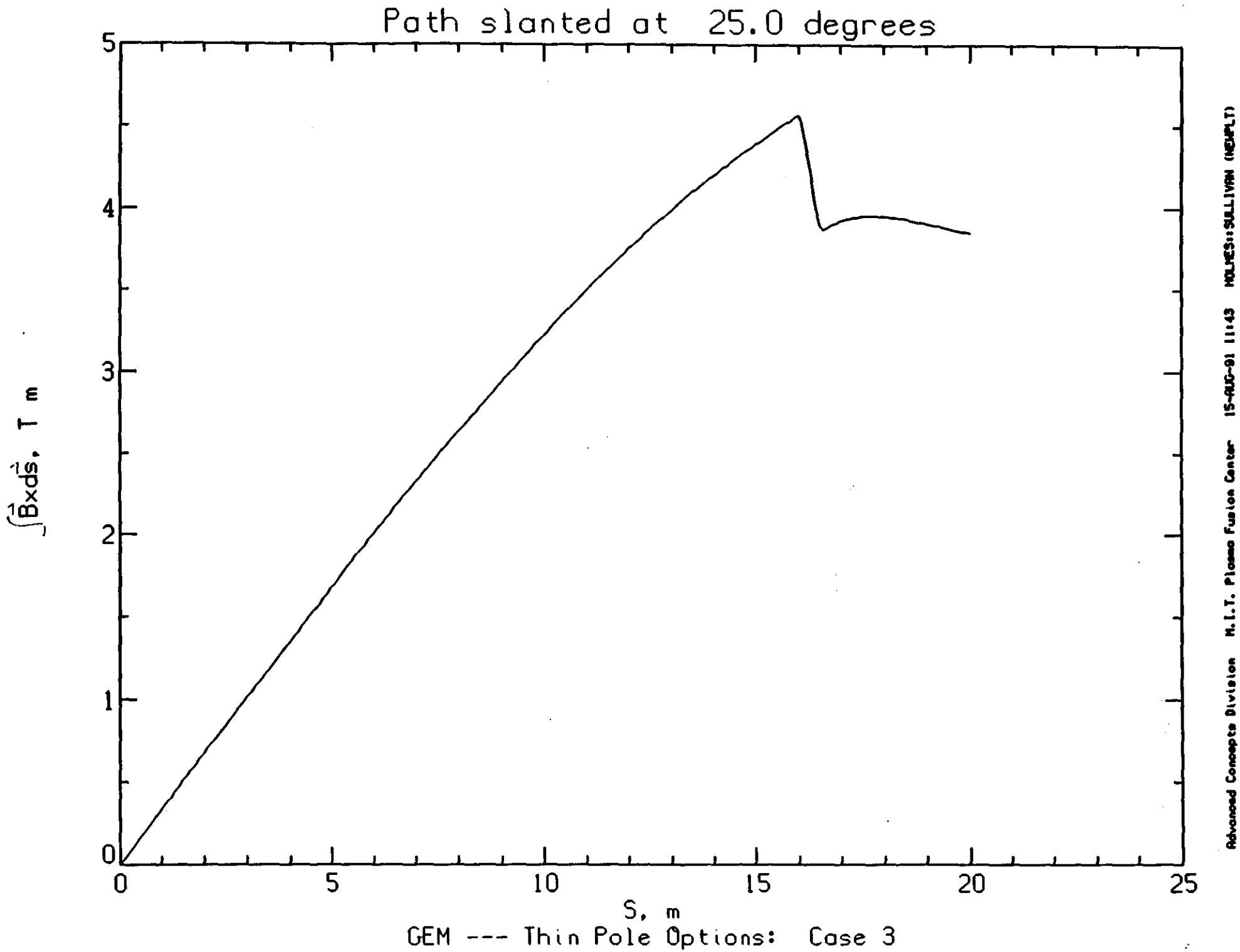
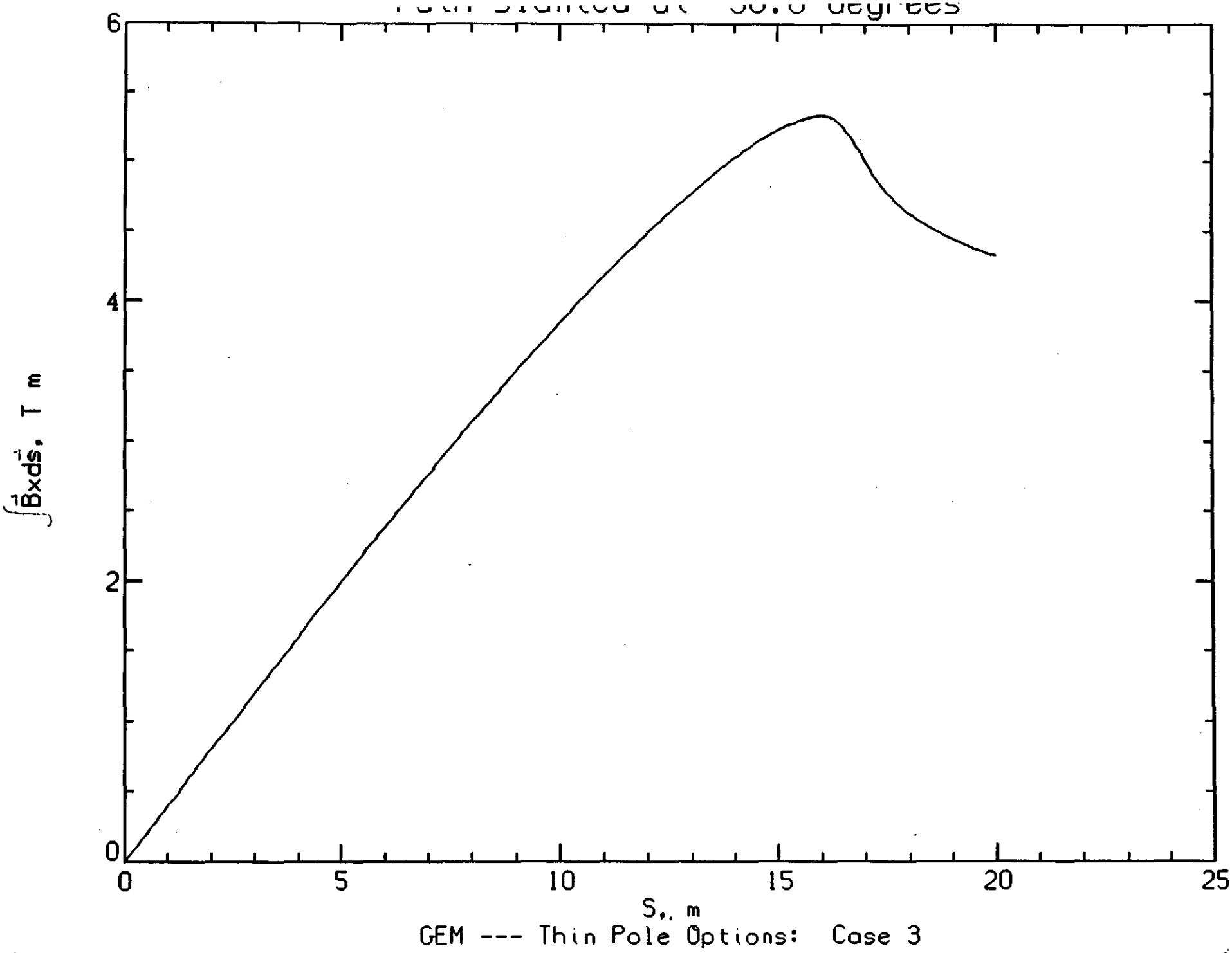
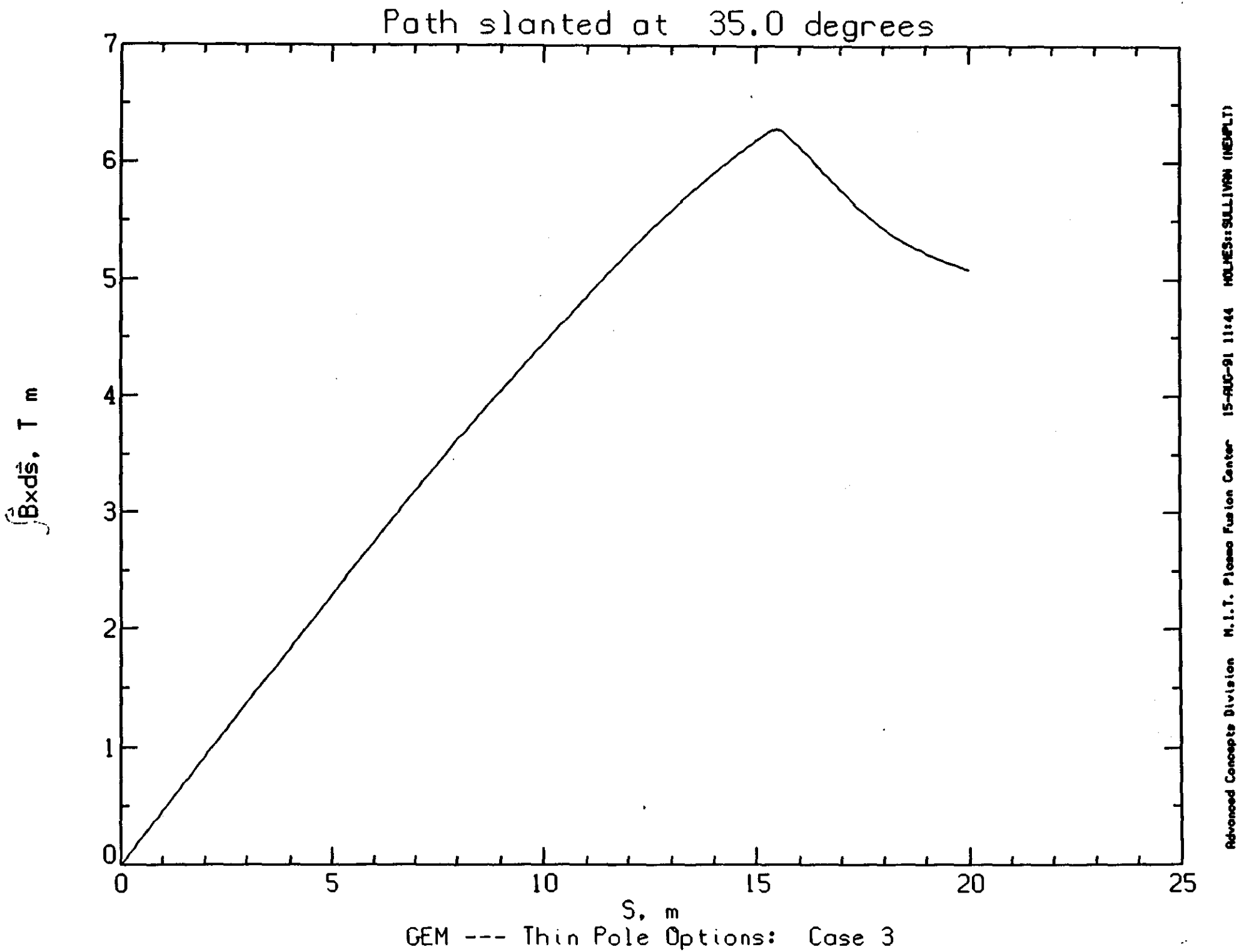
1
2
3
4
0
5
10
15
20
25
S, m
GEM --- Thin Pole Options: Case 3
Advanced Concepts Division M.I.T. Plasma Fusion Center 15-AUG-91 11:43 HOLMES::SULLIVAN (NEMPLT)


Path slanted at 25.0 degrees
$\int \vec{B} \times d\vec{s}$, T m
S, m
GEM --- Thin Pole Options: Case 3
0
1
2
3
4
5
0
5
10
15
20
25
Advanced Concepts Division M.I.T. Plasma Fusion Center 15-AUG-91 11:43 HOLMES::SULLIVAN (MEMPLT)

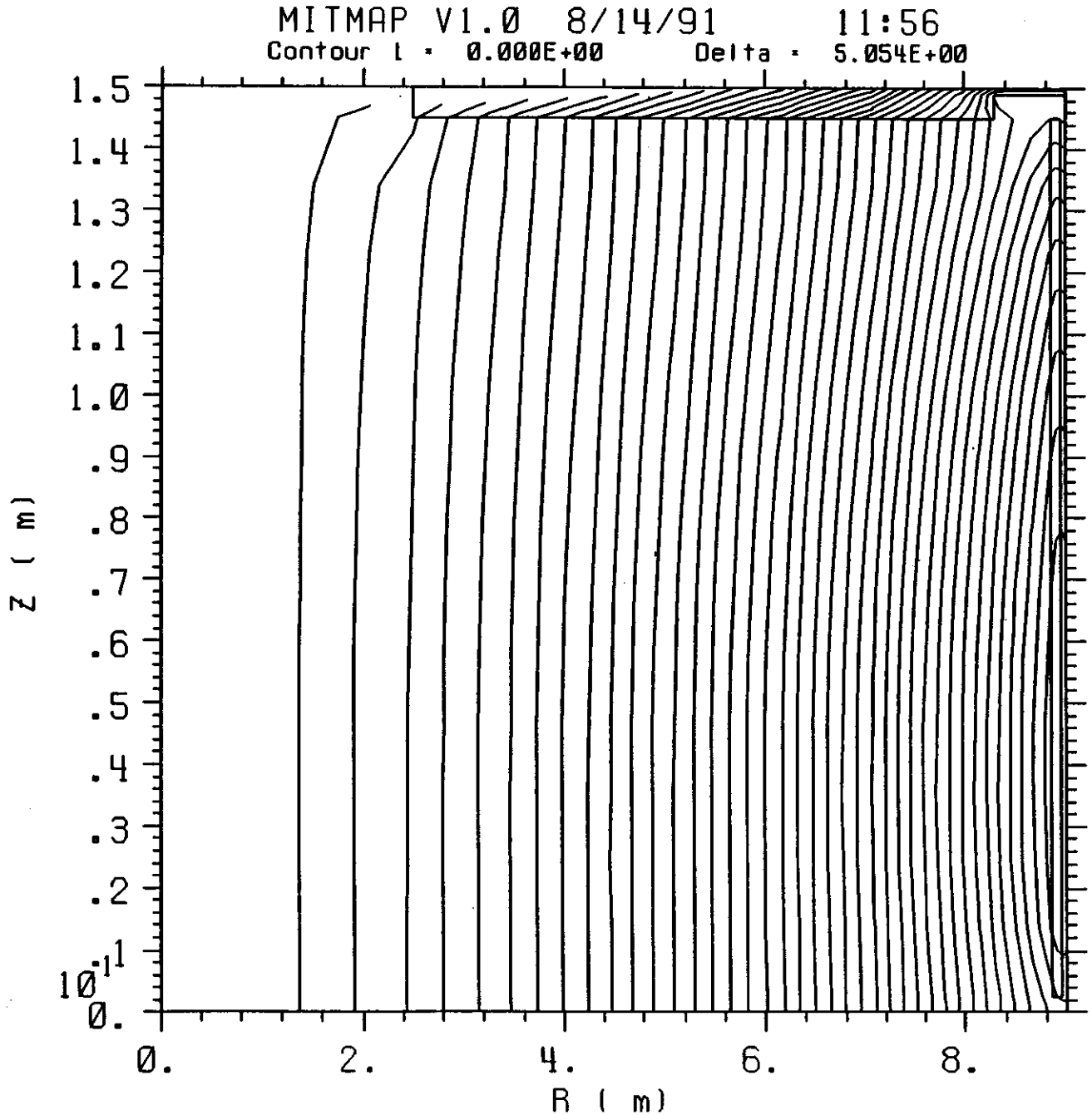


GEM --- Thin Pole Options: Case 3

Advanced Concepts Division M.I.T. Plasma Fusion Center 15-AUG-91 11:43 HOLMES::SULLIVAN (NEMPLT)


Path slanted at 35.0 degrees
$\int \vec{B} \times d\vec{s}$, T m
S, m
GEM --- Thin Pole Options: Case 3
0
1
2
3
4
5
6
7
0
5
10
15
20
25
Advanced Concepts Division M.I.T. Plasma Fusion Center 15-AUG-91 11:44 HOLMES::SULLIVAN (NEWPLT)

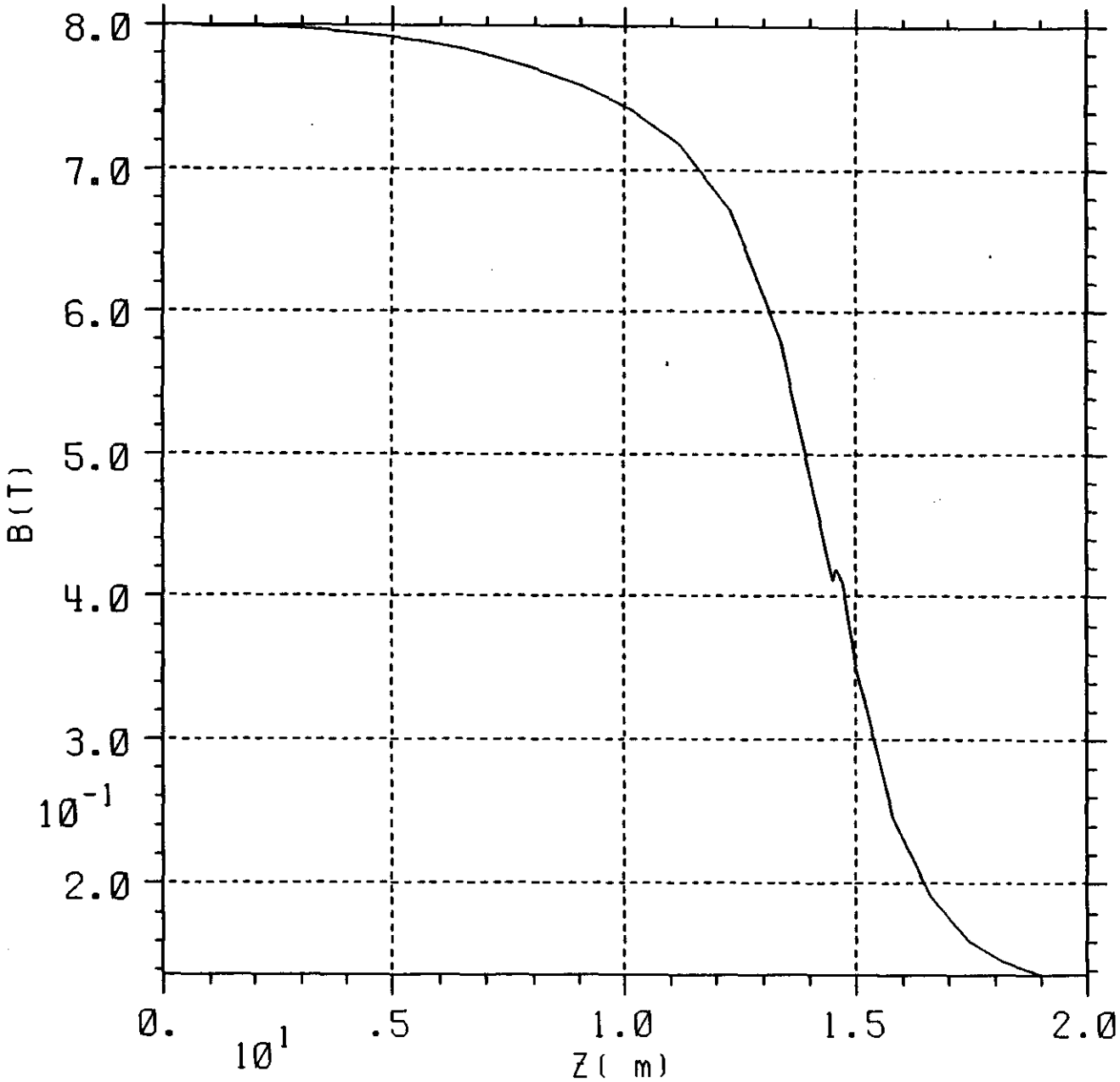
GEM 1 --- Baseline with Full Pole

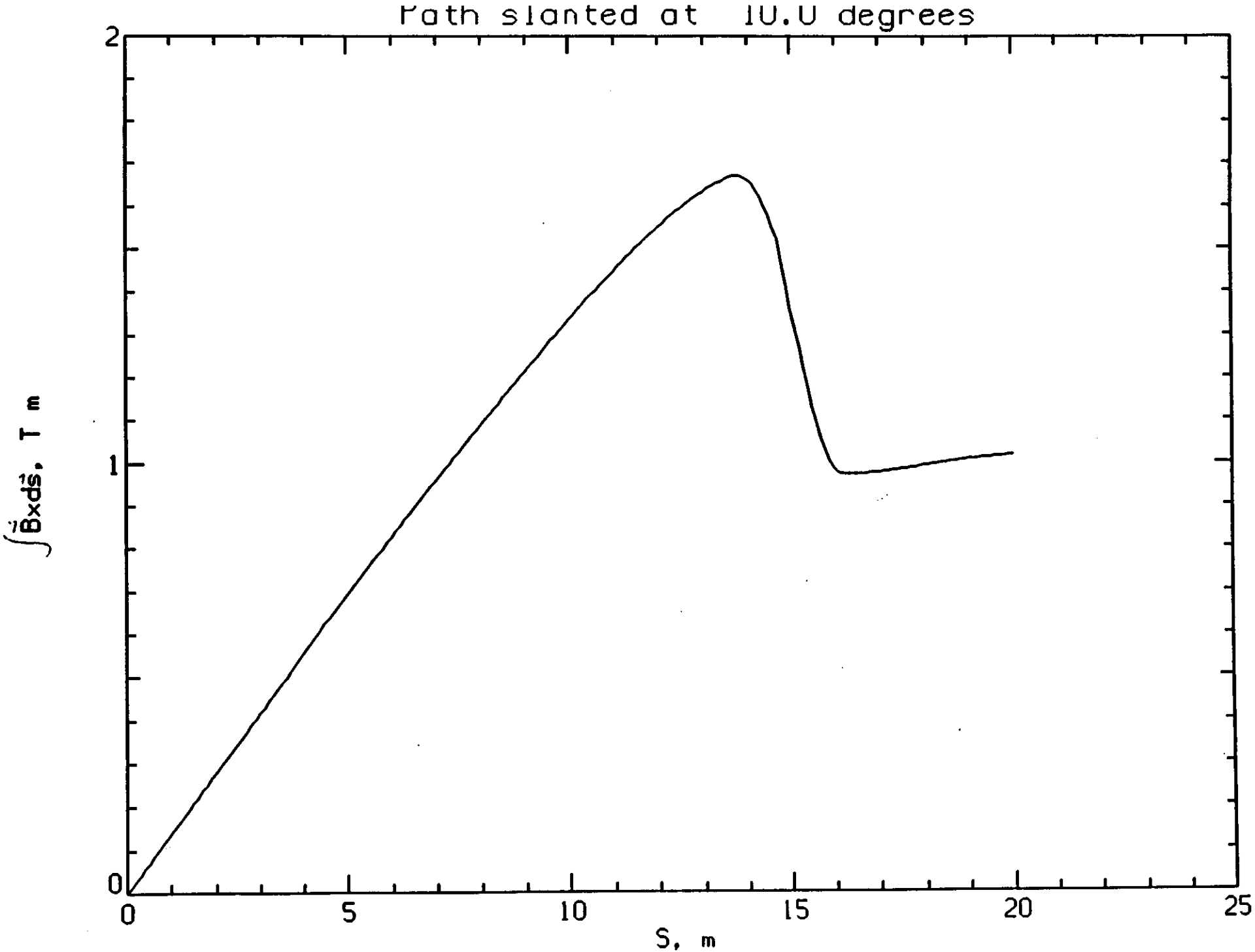


CONTOURS OF CONSTANT FLUX

GEM 1 --- Baseline with Full Pole

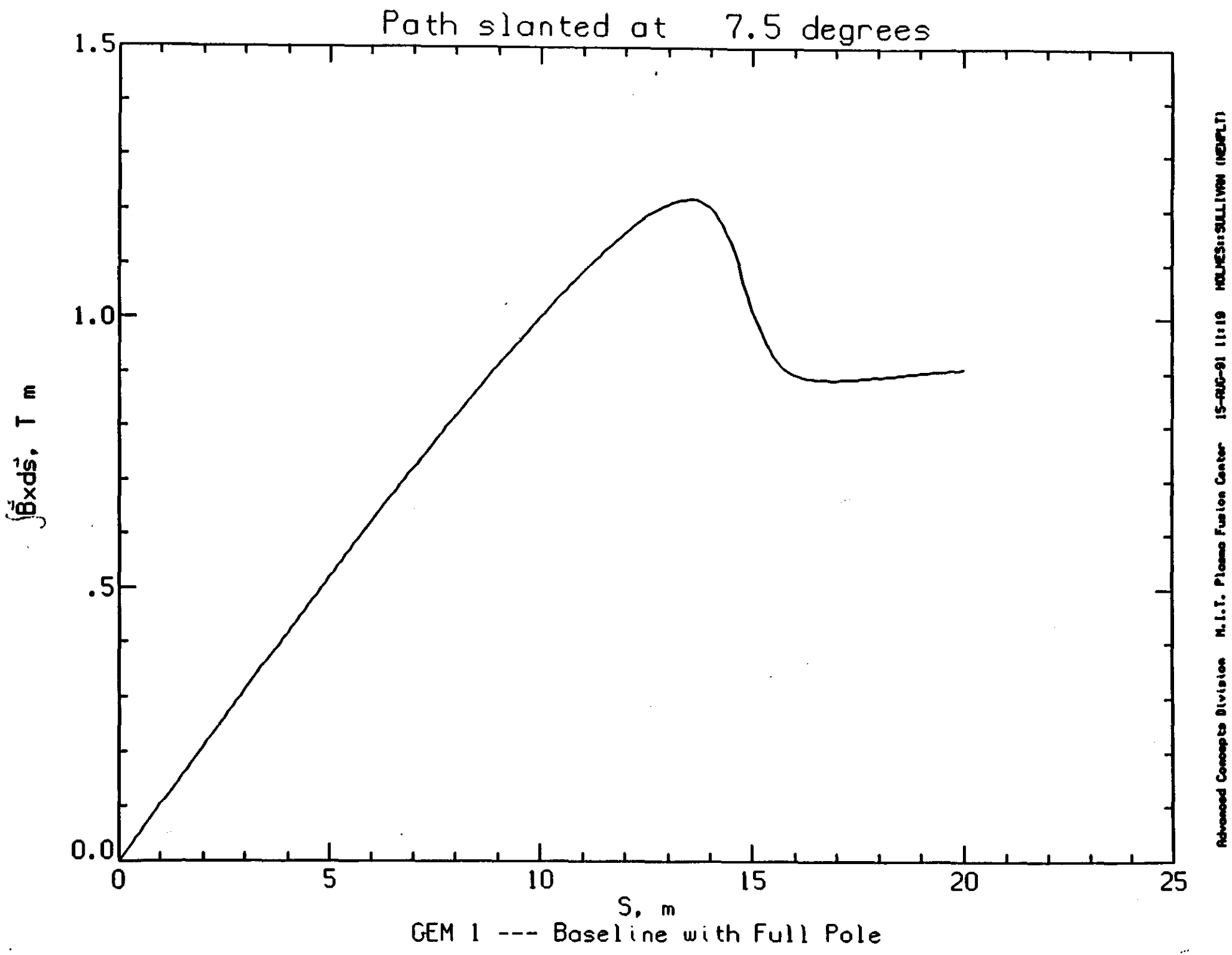
MITMAP V1.0 8/14/91 11:56

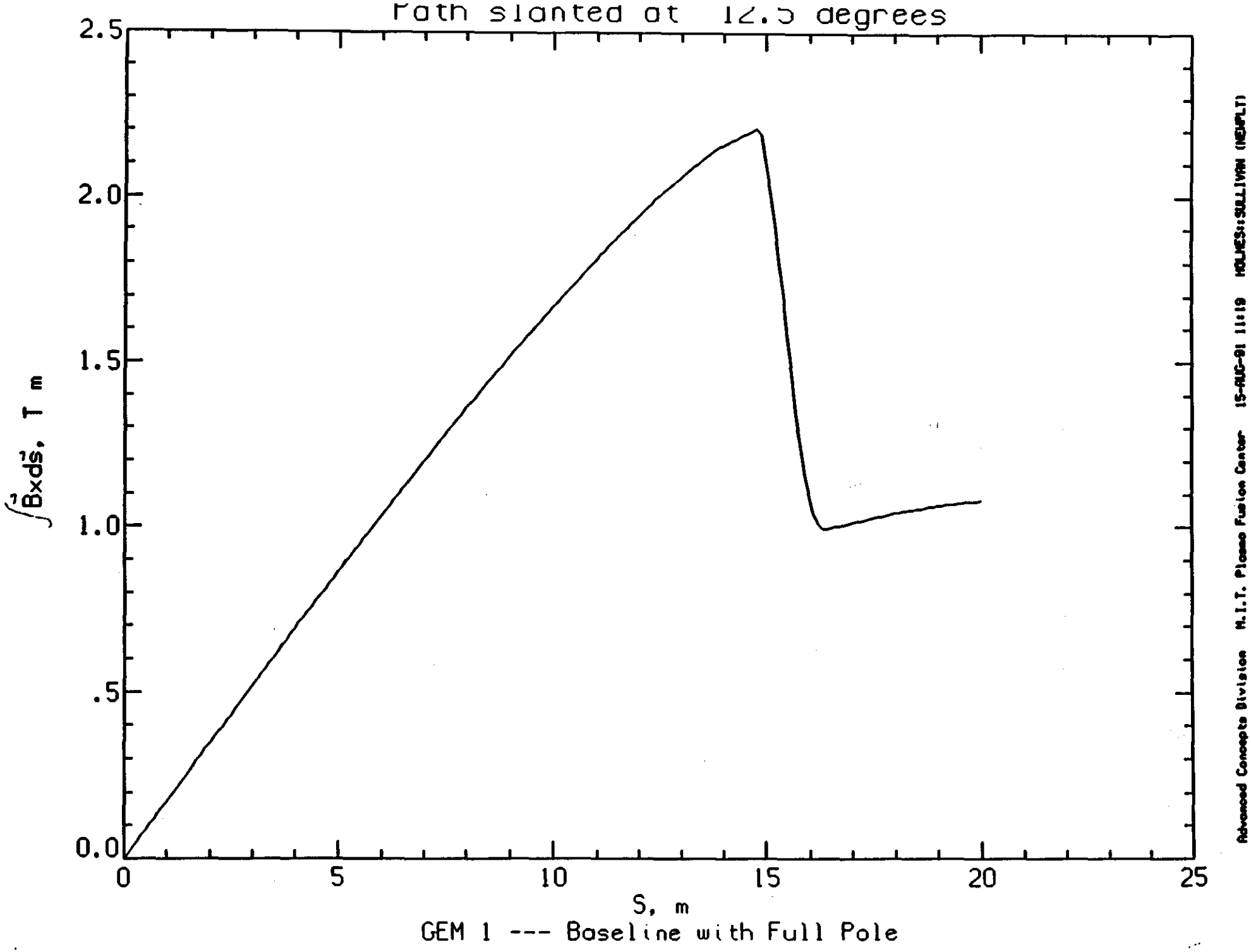




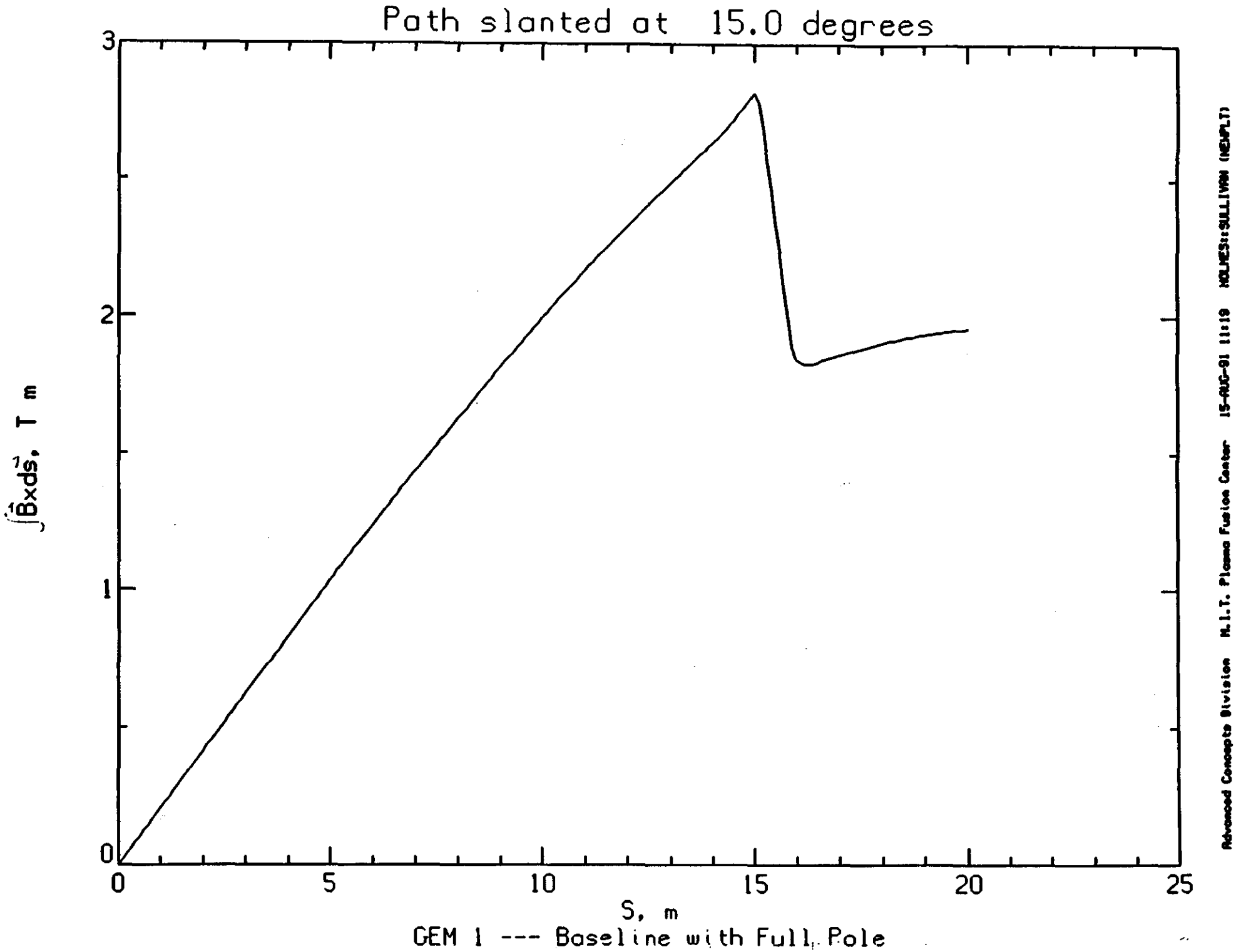
GEM 1 --- Baseline with Full Pole

Advanced Concepts Division M.I.T. Plasma Fusion Center 15-AUG-91 11:19 HOLMES::SULLIVAN (NEWPLT)


Path slanted at 7.5 degrees
1.5
1.0
.5
0.0
0
5
10
15
20
25
S, m
$\int \vec{B} \times d\vec{s}$, T m
GEM 1 --- Baseline with Full Pole
Advanced Concepts Division M.I.T. Plasma Fusion Center 15-AUG-91 11:19 HOLMES::SULLIVAN (NEWPLT)

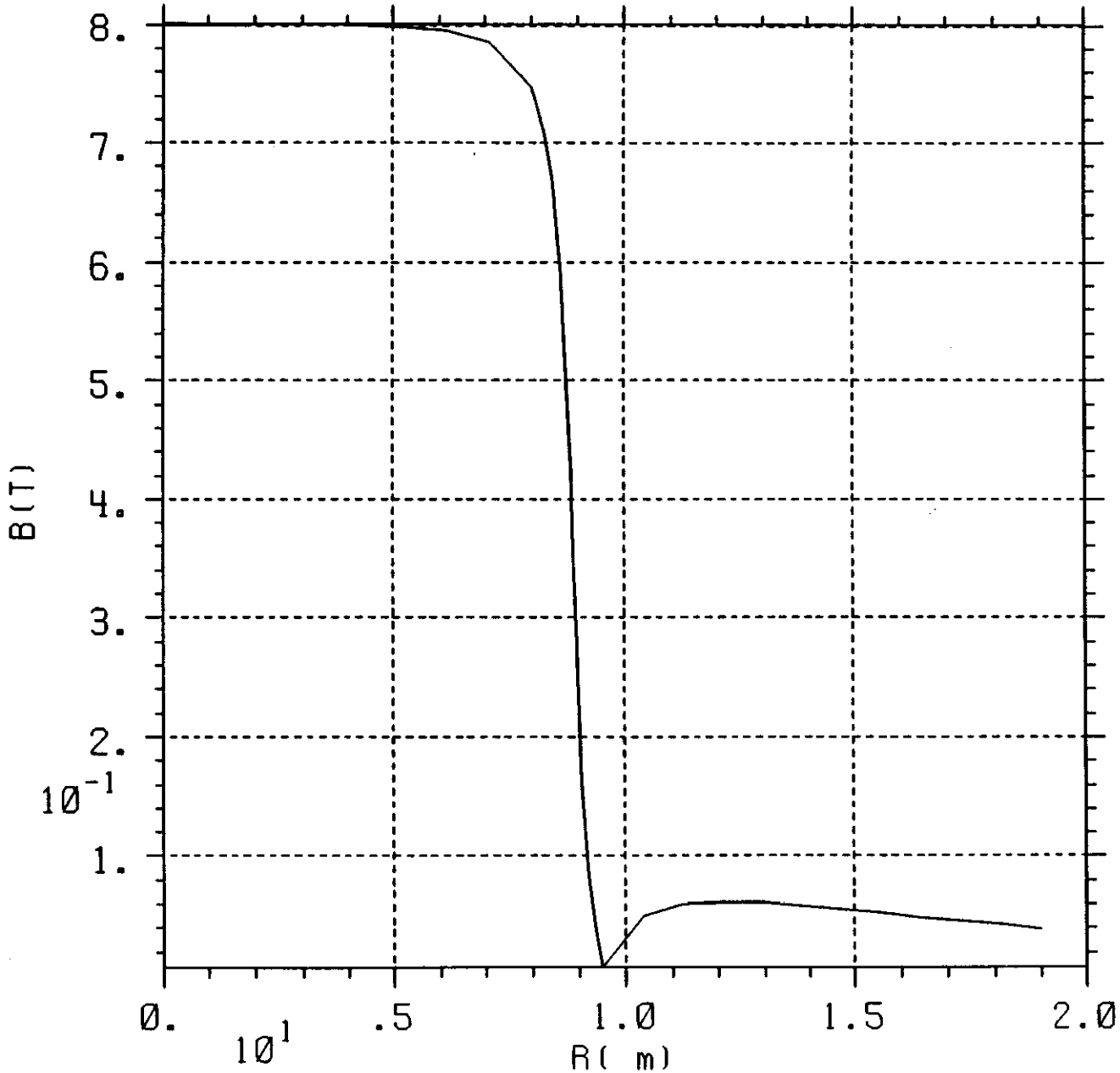


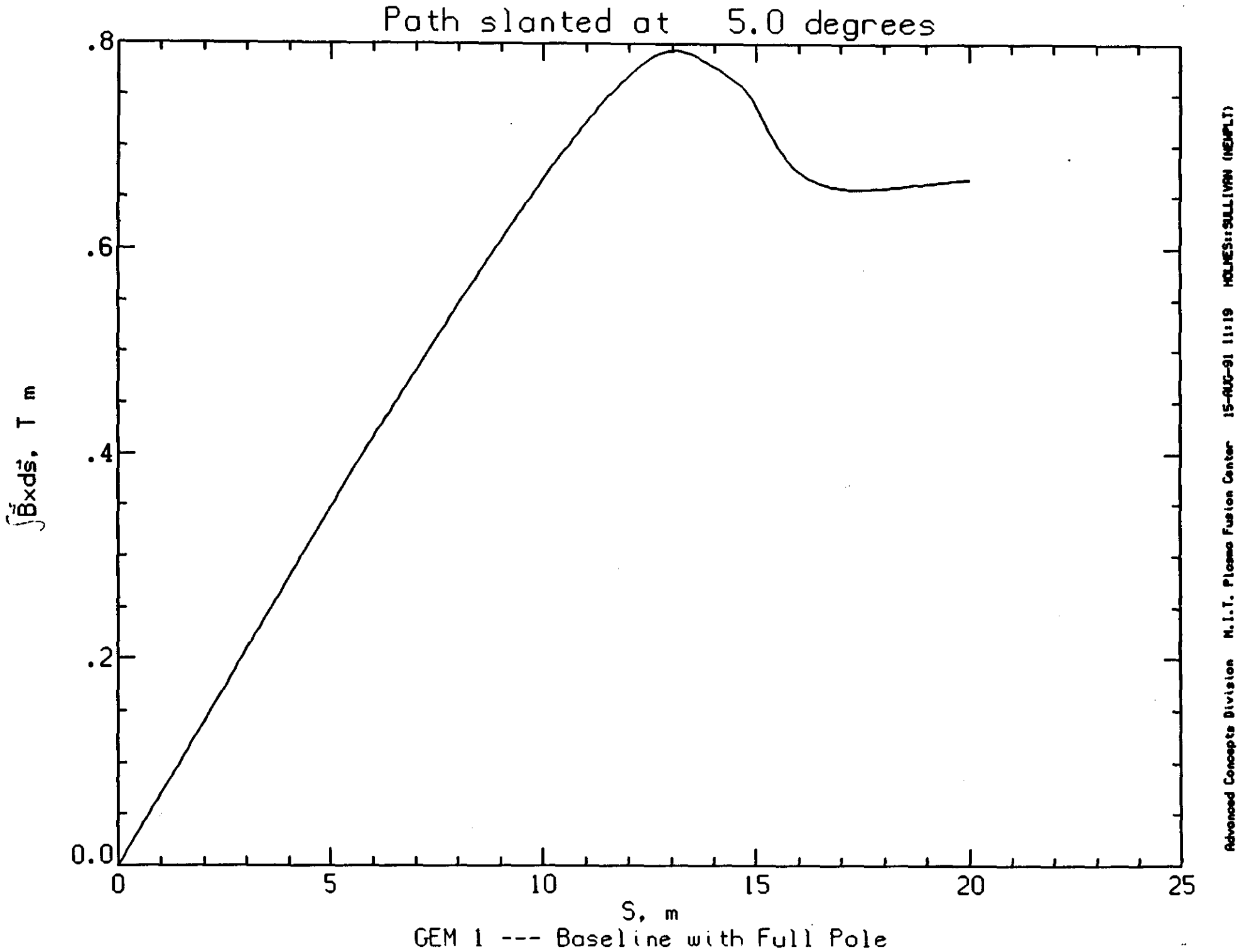
GEM 1 --- Baseline with Full Pole


Path slanted at 15.0 degrees
$\int \vec{B} \times d\vec{s}$, T m
0
1
2
3
0
5
10
15
20
25
S, m
GEM 1 --- Baseline with Full Pole
Advanced Concepts Division M.I.T. Plasma Fusion Center 15-AUG-91 11:19 HOLMES::SULLIVAN (NEWPLT)

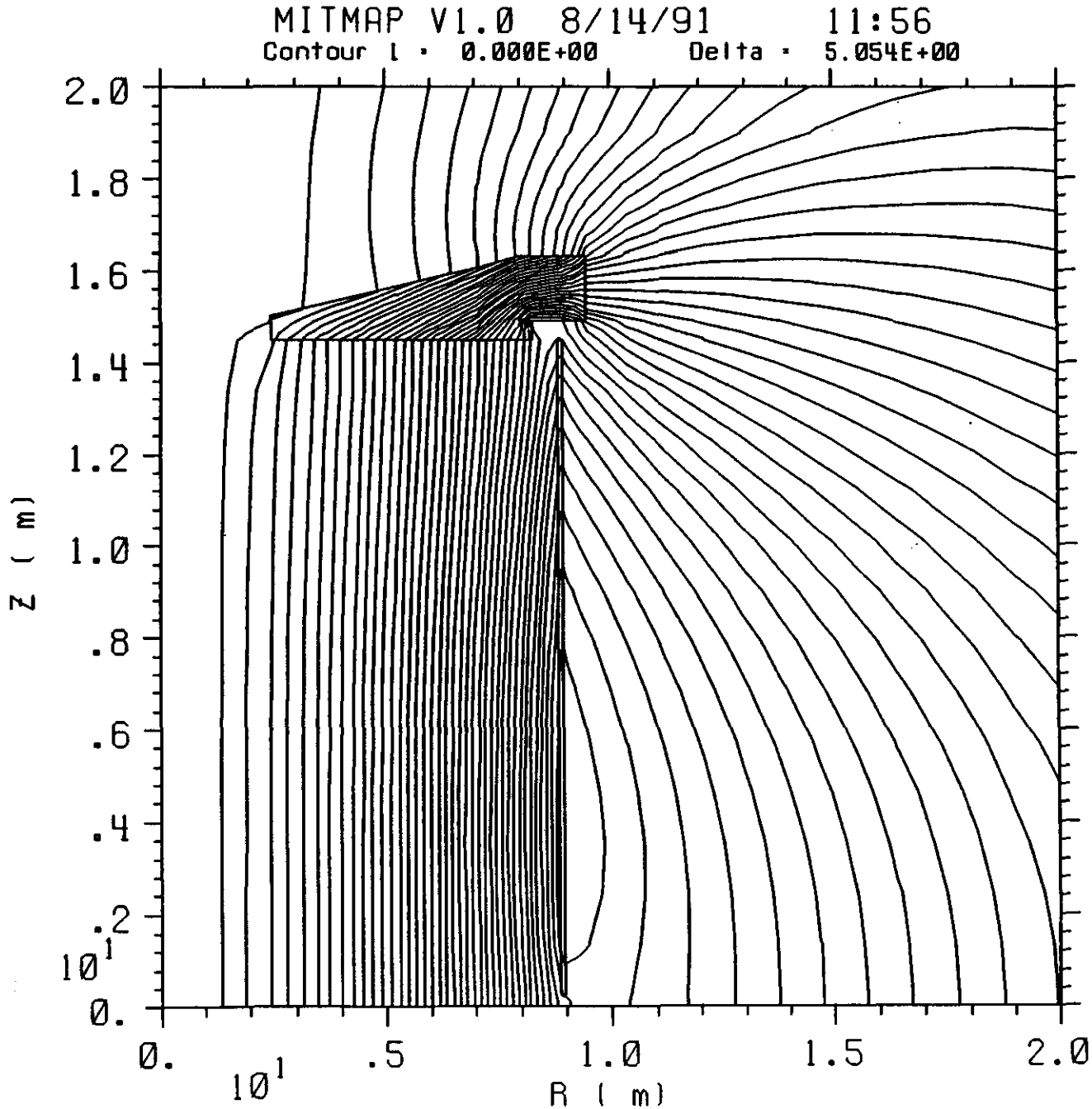
GEM 1 --- Baseline with Full Pole

MITMAP V1.0 8/14/91 11:56

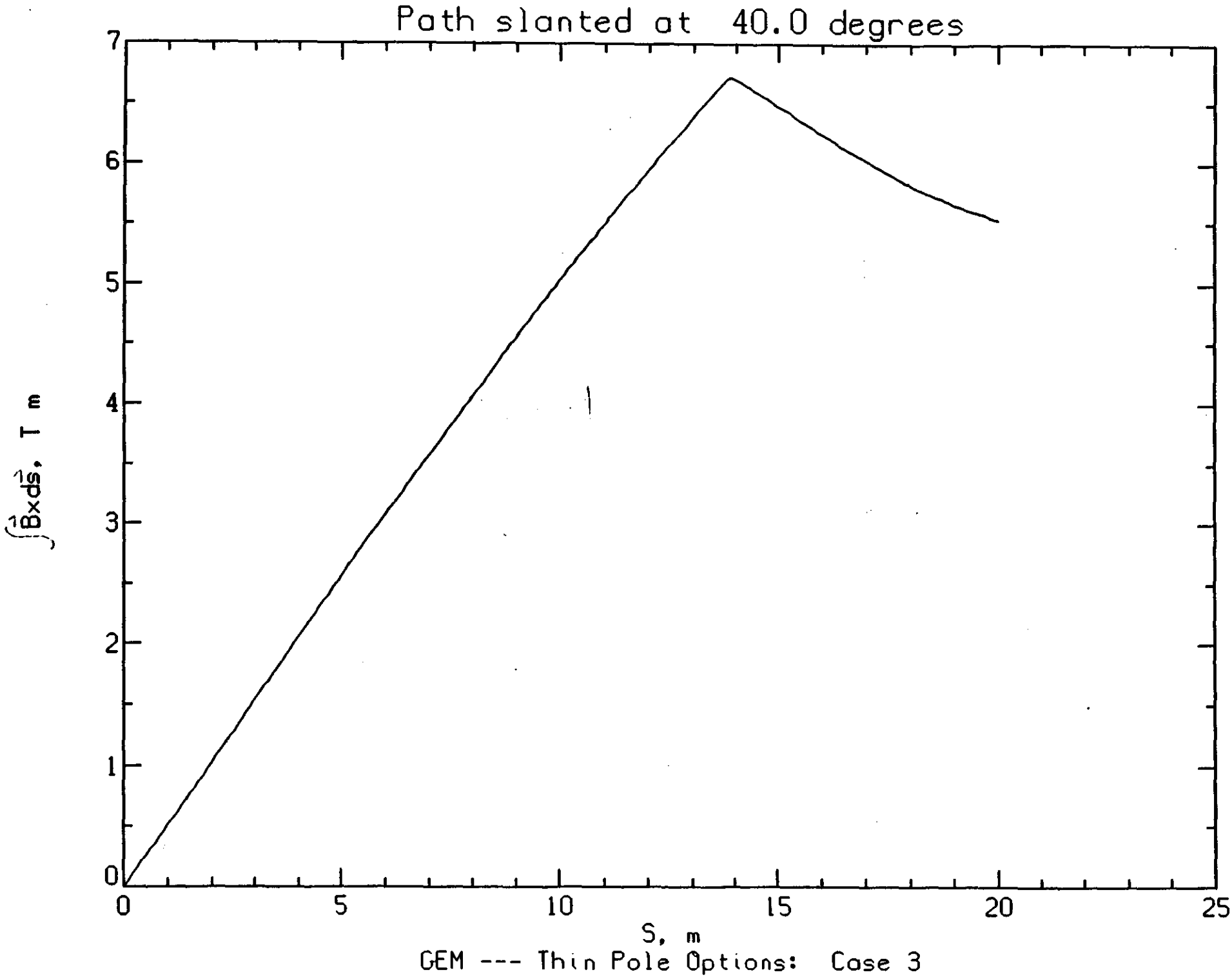



Path slanted at 5.0 degrees
.8
.6
.4
.2
0.0
0
5
10
15
20
25
S, m
$\int \vec{B} \times d\vec{s}$, T m
GEM 1 --- Baseline with Full Pole
Advanced Concepts Division M.I.T. Plasma Fusion Center 15-AUG-91 11:19 HOLMES::SULLIVAN (NEMPLT)

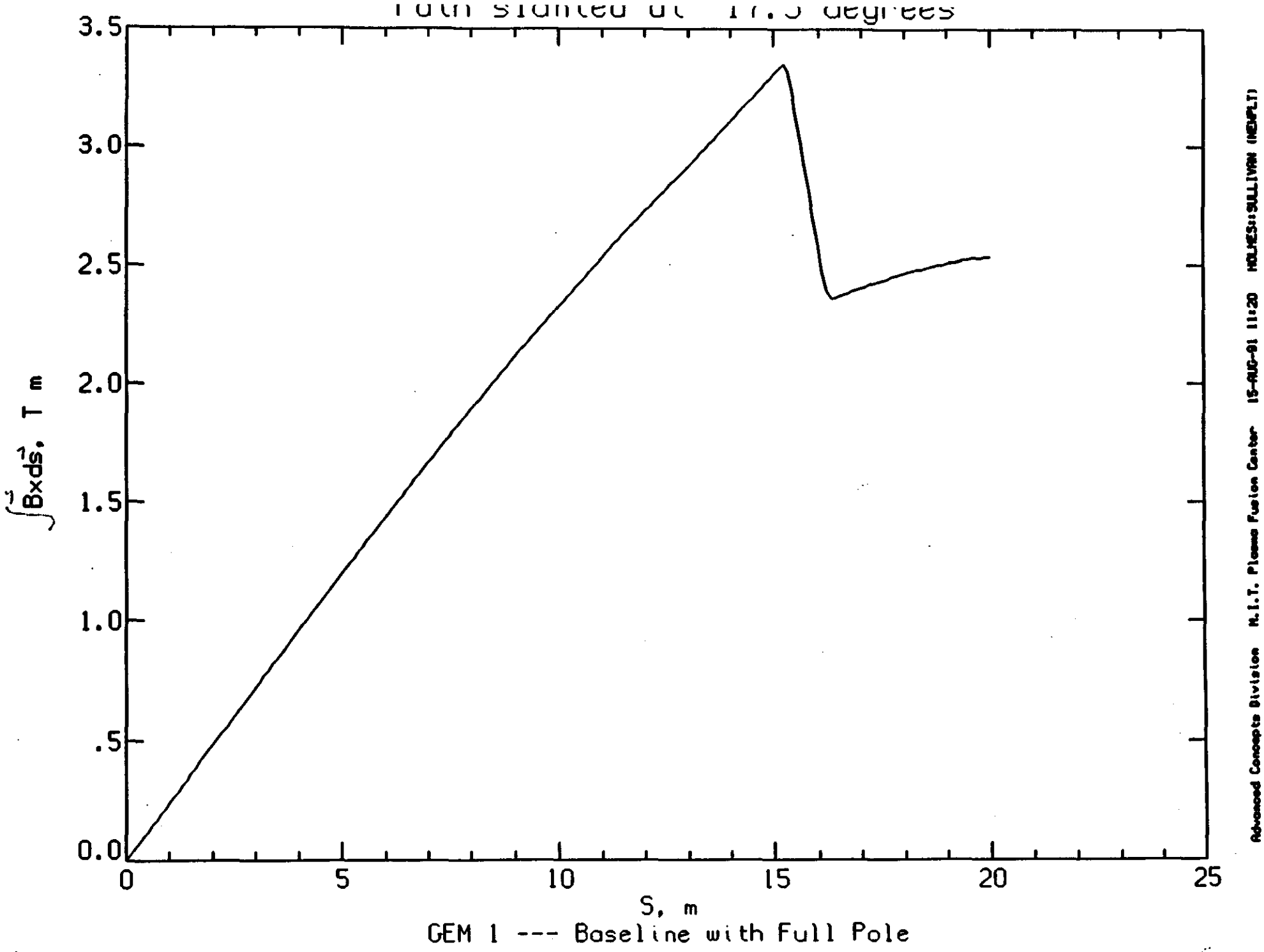
GEM 1 --- Baseline with Full Pole



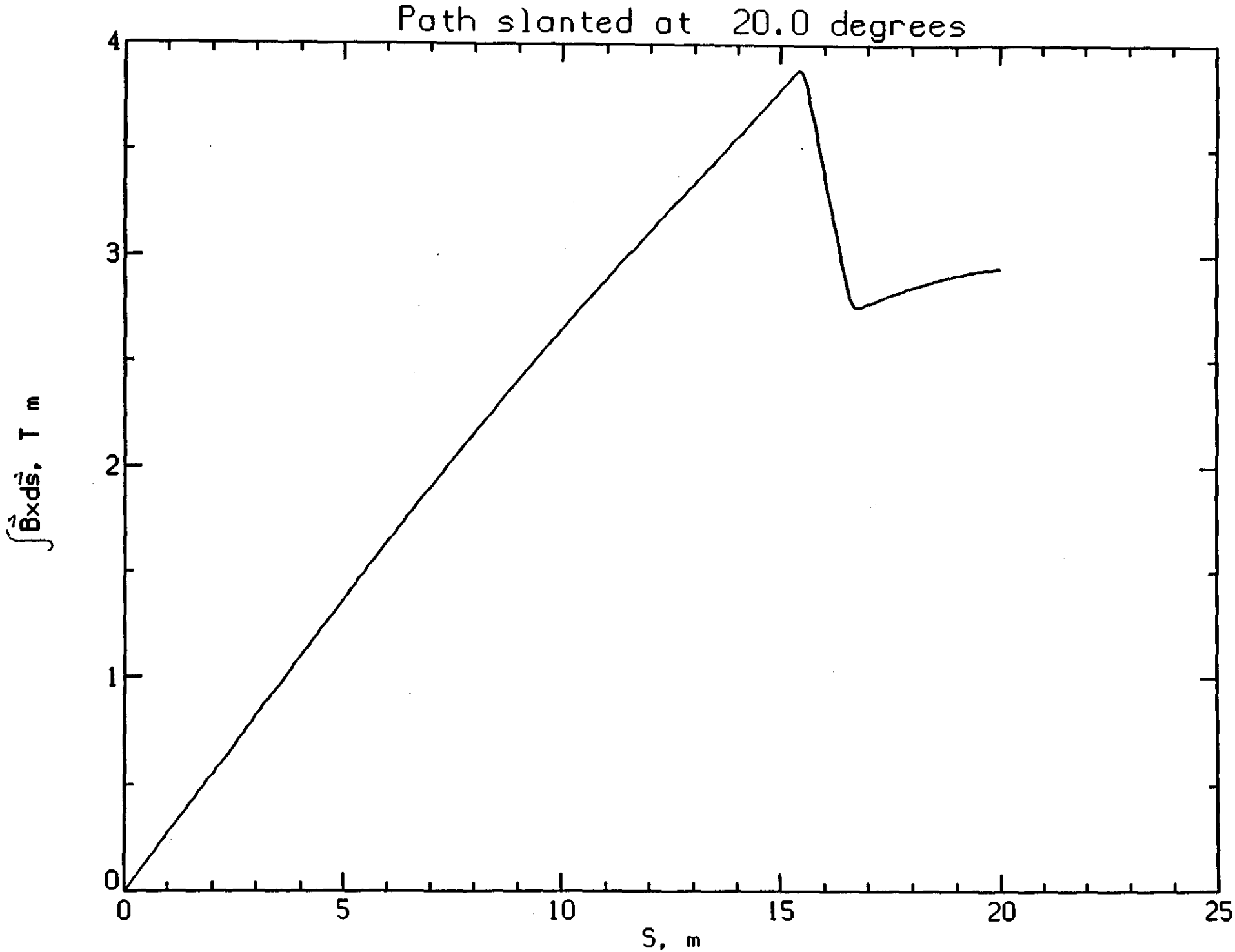
CONTOURS OF CONSTANT FLUX



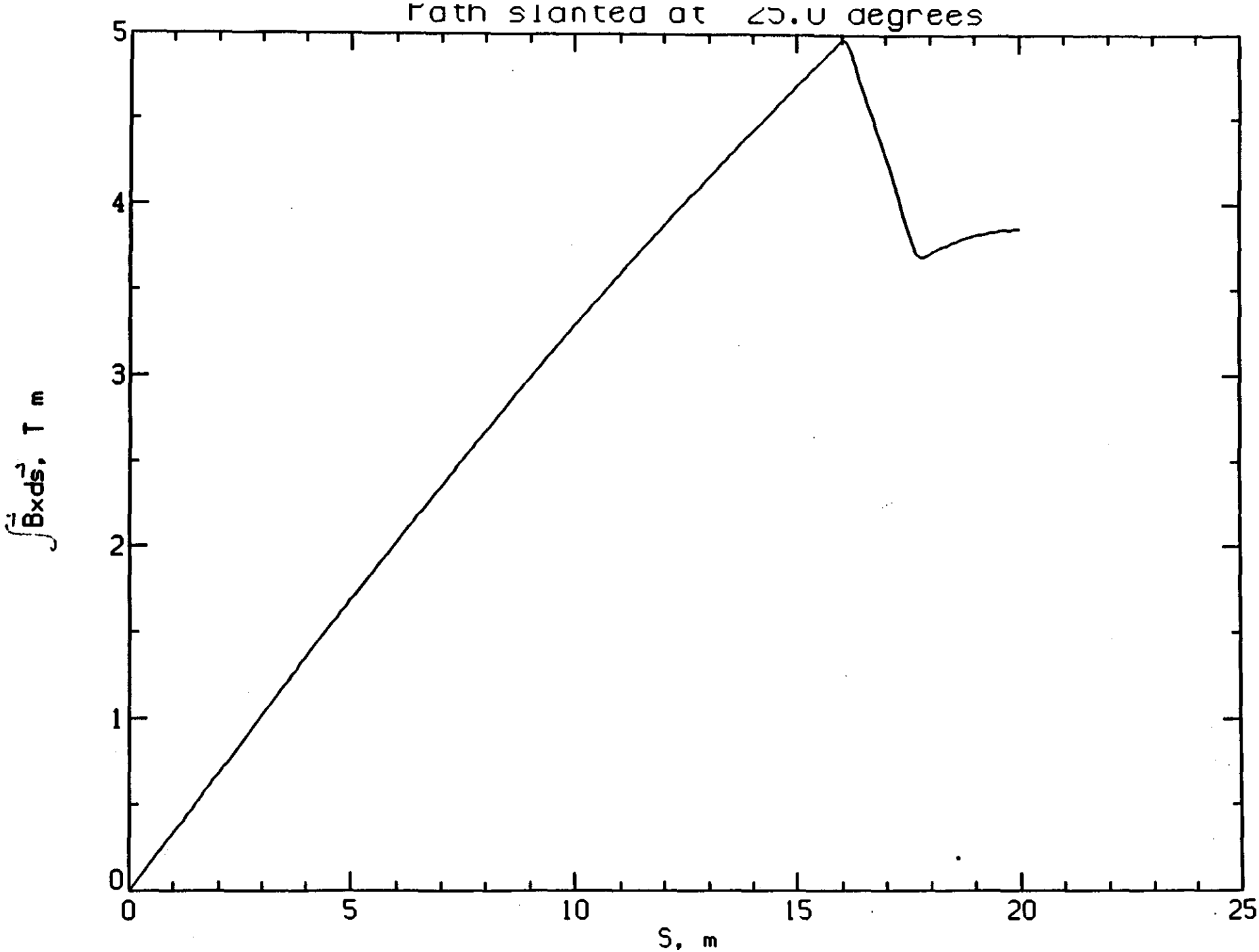
Advanced Concepts Division M.I.T. Plasma Fusion Center 15-AUG-91 11:44 HOLMES::SULLIVAN (NEWPLT)



GEM 1 --- Baseline with Full Pole

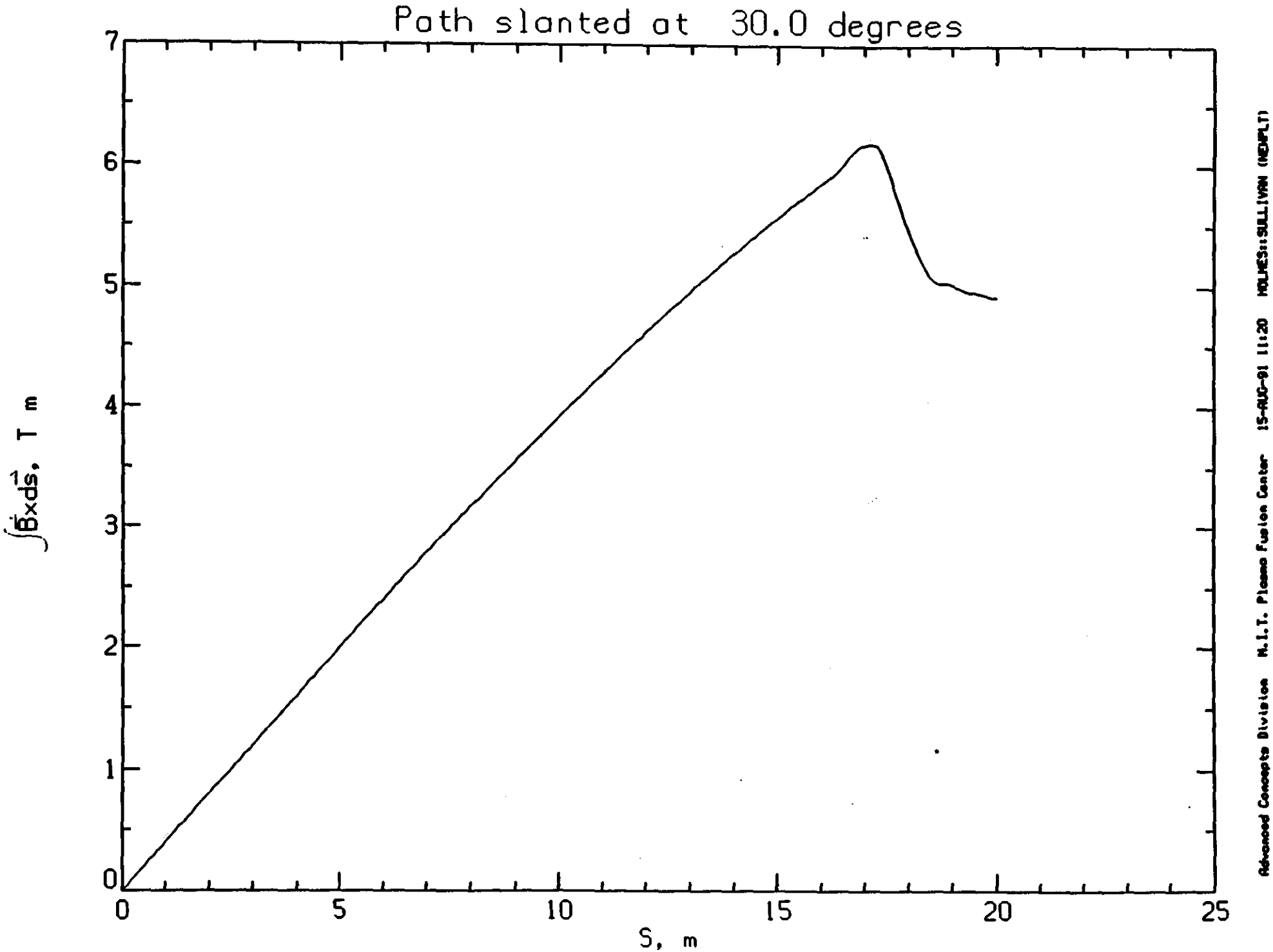


Advanced Concepts Division M.I.T. Plasma Fusion Center 15-AUG-91 11:20 HOLMES::SULLIVAN (NEWPLT)

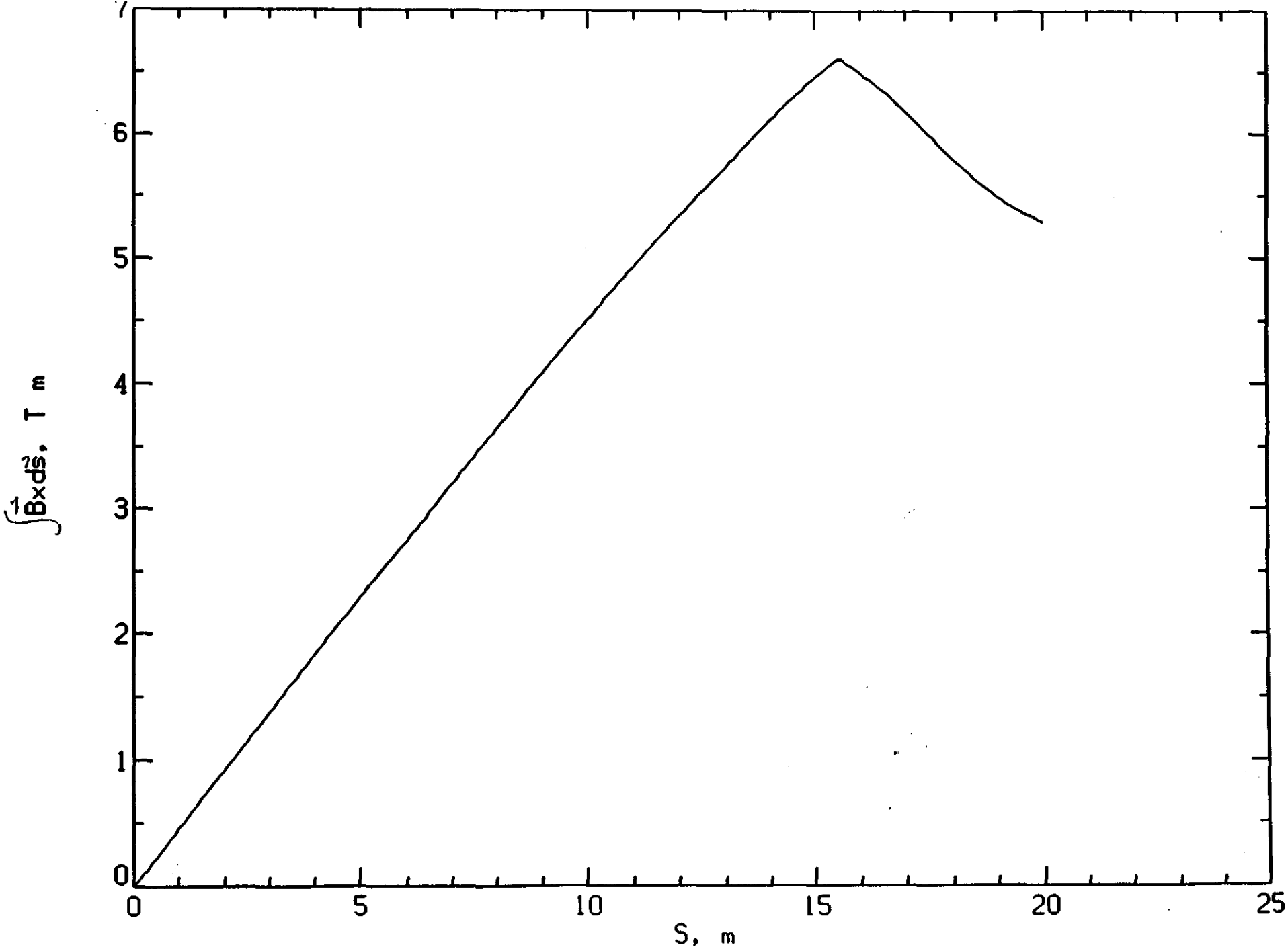


GEM 1 --- Baseline with Full Pole

Advanced Concepts Division M.I.T. Plasma Fusion Center 15-AUG-91 11:20 HOLMES::SULLIVAN (NEMPLT)

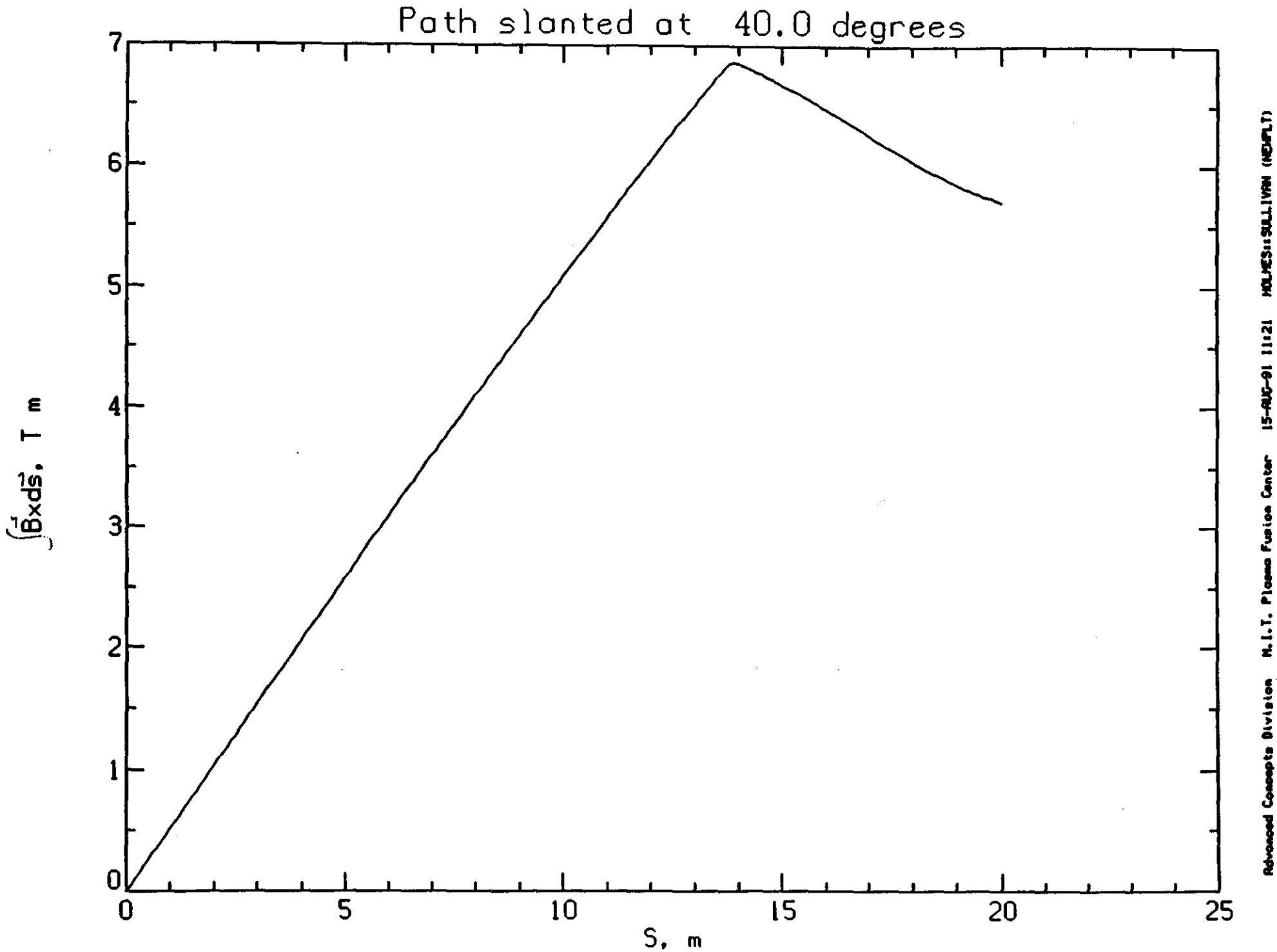


GEM 1 Baseline with Full Pole



GEM 1 --- Baseline with Full Pole

Advanced Concepts Division M.I.T. Plasma Fusion Center 15-AUG-91 11:20 HOLMES::SULLIVAN (NEWPLT)


Path slanted at 40.0 degrees
$\int \vec{B} \times d\vec{s}$, T m
S, m
0
1
2
3
4
5
6
7
0
5
10
15
20
25
Advanced Concepts Division M.I.T. Plasma Fusion Center 15-AUG-91 11:21 HOLMES::SULLIVAN (NEWPLT)